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Batteries, Battery Management, and Battery Charging Technology

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Glossary

Alternating current (AC) Usually in the form of a sine wave, the bidirectional current flow continually reverses. Typically, AC will have a zero mean (average) and a nonzero RMS value. In the USA, most “grid” electricity is generated and distributed in the form of 60 Hz sinusoidal waveform. In other areas of the world, 50 Hz is commonly used.

Amp-hour (Ah) A unit of electric charge, the amount of current delivered for 1 hour.

Battery A group of one or more cells electrically connected in series and/or parallel combinations to achieve higher voltage or current than what is capable from a single cell.

Battery management system (BMS) An electronic device or system that monitors and controls a rechargeable battery. Parameters measured may

include cell temperature, voltage, and current. From this data, the BMS can compute the state of charge of the battery and estimate the state of health, remaining cycle lives, or remaining service life. Typically, a BMS system will include the ability to communicate with a host system and battery charger. The BMS may also contain sensors and circuitry for protection such as over-current, over-temperature, or over-voltage.

Battery pack A group of batteries or individual cells electrically connected in series and/or parallel combinations along with the required electrical interconnections, mechanical packaging, thermal management, and sensing circuitry. Because it is a self-contained assembly, a battery pack can be easily swapped in and out of the application.

Battery string Series-connected batteries used to produce a higher voltage. The same current passes through all the cells, but each cell voltage can vary. Charge balancing becomes a significant issue for a long string of 50 or more cells.

C-rate The rate at which a battery can deliver or accept current, stated in terms of the rated capacity of the cell in amp-hours. This may also be referred to as the hour rate, such as the 1-h rate.

Cell An individual electrochemical device that converts between chemical energy and electrical energy. The cell construction, open circuit voltage, energy, and power density, all depend on the chemistry of the cell (see section “[Battery Chemistries](#)”).

Coulombic efficiency Ratio of charge delivered by a rechargeable battery during discharge cycle to the charge stored during charge cycle.

Depth of discharge (DoD) An alternate method to indicate the state of charge of the battery; it is the reciprocal of SoC.

Direct current (DC) Unidirectional current that continually flows only in one direction. Sources such as batteries, fuel cells, and solar cells produce electricity in the form of direct current.

Memory effect An effect observed particularly in nickel cadmium batteries in which the cells gradually lose capacity when subject to repeated partial discharges followed by complete recharge cycles. This electrochemical effect is different than the loss of capacity due to aging and use. In some cases, a series of full discharge/recharge cycles can restore some or all of the lost capacity due to the memory effect but not due to cycle life or aging.

Proportional-integral (PI) controller A type of linear feedback control in which an error signal is calculated as the difference between a measured signal and the desired reference set point. The controller attempts to adjust the operation of the process using a weighted combination of the present error (proportional term) and accumulated past error (integral term).

Primary battery One-time-use batteries not capable of being recharged. They are discarded or preferably recycled once the stored energy has been depleted. These types of batteries will not be considered in this article.

Root mean square (RMS) A scalar quantity that is computed from the square root of the sum of the squares of a dataset and is commonly used to represent a voltage or current over one cyclical period. Average power is the product of the RMS current and RMS voltage.

Secondary battery Commonly referred to as rechargeable batteries, they can be repeatedly recharged electrically by passing current through them in the opposite direction to that of the discharge current. Secondary batteries are of significant interest for their ability to store and supply energy and are the focus of this article.

Self-discharge rate The rate at which a battery discharges, or loses stored energy, due to internal cell reactions.

SLI batteries Starting, lighting, and ignition (SLI) batteries are used in automobiles. These batteries are usually characterized by a high discharge rate.

State of charge (SoC) Defined as the capacity left in a battery expressed as a percentage of some reference. SoC of a battery is usually expressed as a percentage of the current battery capacity when it is fully charged.

State of health (SoH) A metric that reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery. It takes into account factors such as charge acceptance, internal resistance, voltage, and self-discharge. It is an estimate rather than a measurement.

Watt-hour (Wh) A unit of energy, the amount of power delivered for 1 h. It is equivalent to 3,600 Joules of energy.

Definition of the Subject

Batteries, both primary and rechargeable, are important energy storage devices ubiquitous in our daily, modern lives. Whether in our handheld portable electronics, conventional or hybrid/electric cars, or in the electrical “grid,” battery technology will continue to evolve as technology improvements increase storage capacity and lifetime and reduce cost.

Introduction

Batteries are perhaps most synonymous with portable power such as flashlights and personal electronics like cell phones, music players, and laptops to name a few modern examples. We have become trained to monitor the battery “bars” to determine how much more we can talk, e-mail, or surf the “net.” Batteries are far more prevalent, however, and they tend to be underappreciated, such as the ones in our automobiles which perform dutifully until suddenly, usually after years of neglect, they fail to start our car. An electrical power system is the ultimate in just-in-time manufacturing in that electricity generation and consumption must be perfectly balanced at all times. This imposes difficult operating constraints on the system when variability on both the load side and source side exists, such as with renewable energy sources like wind and solar. Therefore, energy storage is important to ensure that electricity can be generated and energy stored generated when the source is available, and the load can continue to be supplied when the variable, renewable energy source is insufficient. While there are many technologies for energy storage, batteries play an important role to improve the electric power system asset utilization, energy availability, reliability, and performance. Several large-scale, high-energy battery technologies hold

promise of providing economical energy storage for a wide range of these power system and energy management applications.

This chapter will discuss issues related to batteries, battery charging, and battery management. The first section will provide an overview of the different types of battery chemistries. The focus in this chapter is on rechargeable batteries which can accept, store, and then deliver energy at a future point in time. Subsequent sections will discuss circuits to charge and manage the batteries.

A detailed description of internal construction of the individual cell is beyond the scope of this chapter, but it is sufficient to consider that a battery is typically comprised of electrodes, electrolyte, and some form of case or enclosure as shown in Fig. 1. Various materials are commonly used, each with advantages and disadvantages. The voltage, current rating, and storage capacity are all functions of the material and construction.

Battery Failure

Some of the most common causes for battery failure are short circuiting of battery terminals, improper charge control while charging secondary batteries,

improper polarity connections while charging a battery, and a long period of use. Internal failure modes include thermal runaway which is a major problem in lead-acid batteries, loss of electrolyte by gassing, mechanical damage, and warping of plates due to an excessively high rate of discharge.

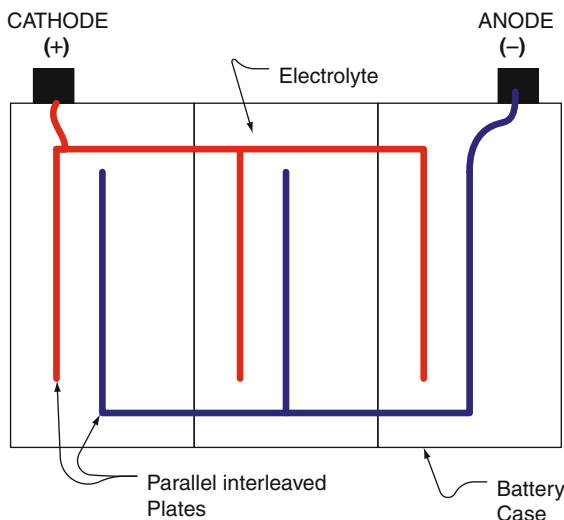
Methods of Charging

Float charge is most commonly used for non-sealed lead-acid batteries, which can tolerate sitting at an elevated voltage for prolonged periods of time. The original meaning of the term stems from the telecom industry's jar batteries in which the liquid electrolyte was exposed to the atmosphere and the batteries "sat on float" at a continuous elevated voltage to be sure they were fully charged when called upon to back up the telephone equipment. In this mode of operation, the charging current depends on the state of charge of the cells, and the current gradually declines to a minimum value as the cells become fully charged. Float charging could result in continuous out gassing which reduces the level of water in the electrolyte. Hence, float charging of lead-acid batteries often requires "watering" of the batteries to maintain the level of electrolyte.

Trickle charge is used to maintain a battery at a full state of charge by supplying a small current to offset the self-discharge characteristics of the battery. Some battery chemistries, like the lead-acid varieties, have relatively high self-discharge rates and can lose their ability to hold a charge when stored discharged for a long period of time due to sulfation, the crystallizing of the lead sulfate. A trickle charger, sometimes called a "battery tender" is often used in automobile, boats, motorcycles, RV and other seasonal equipment where the battery can sit for months without use.

Bulk charge involves restoring the majority of the energy storage capability of a battery. Hence, a bulk charge may be followed by an equalizing charge.

Equalization charge is the final stage of charging for a series-connected battery string in which the SoC of individual cells are forced to the same value. For lead-acid batteries, this can be as using a higher charging voltage. The cells with higher SoC begin to outgas while the weaker cells "catch up." Other battery chemistries



Batteries, Battery Management, and Battery Charging Technology. Figure 1

Conceptual illustration of a lead-acid battery with parallel, interleaved plate that comprises the anode and cathode. The electrolyte can be a liquid or a gel, and the enclosure can be vented or sealed

cannot tolerate overvoltage charging. Charge balancing techniques will be described in detail in the next section.

Rapid charge involves quickly recharging a battery at a high C-rate. Depending on the battery chemistry, this mode of charging may only replace a portion of the full capacity. It is usually imperative to monitor the cell temperature rise during rapid charging to avoid excessive outgassing or thermal runaway.

Regardless of the mode of charging, the charging types include constant-current charging and constant-current–constant-voltage charging (constant-current charge until current attains a flat profile, then constant-voltage charging takes over).

Battery Chemistries

A wide variety of battery electrochemistries are available today. While there is a clear evolution of technological progress, each technology has advantages and disadvantages that make them more or less suited for different applications. This section presents an overview of commonly available technologies and explores their general characteristics, advantages and disadvantages, and charging considerations.

Lead Acid

General Characteristics

Lead-acid batteries are by far the most common battery type and represent approximately 40–45% of the total global battery sales. Lead-acid batteries are available in large quantities and in a variety of sizes and designs. They are manufactured in sizes from smaller than 1 Ah to several thousand Ah. Design variations to electrode plates enable them to perform as batteries with high discharge rate and low-energy (automobile starting applications) and also for deep-cycle applications with moderate discharge rates.

The world's largest battery-based energy storage system is a 40-MWh battery located in Chino, California. It uses individual industrial-size lead-acid cells in series and parallel connection to make a 10-MW system capable of delivering energy into the utility grid at 2,000V and 8,000A for 4h.

Advantages and Disadvantages

Advantages include:

- One of the main reasons for the popularity of lead-acid batteries is that they can be manufactured on a local basis worldwide with high rates of production.
- Traditionally, they have been used as starting-lighting-ignition (SLI) batteries in automobiles, though now they are being slowly phased out by high-performing nickel cadmium and nickel metal hydride batteries.
- They have a high cell open-circuit voltage of 2.0 V which is one of the highest for aqueous electrolyte systems.
- SoC estimation is very easy in the case of lead-acid batteries. The specific density of electrolyte bears a direct relation to the SoC of the battery.
- It provides good charge retention for intermittent charge applications.
- Cell components can be easily recycled.
- They are very cheap compared to other secondary battery designs.
- They are also available in maintenance-free designs.

Disadvantages include:

- Lead-acid batteries require frequent maintenance. These batteries lose water while in operation, and the water level needs to be replenished.
- As they employ lead in their construction, they are usually heavy and not conducive for portability.
- Lead-acid batteries have a relatively low cycle life (50–500 cycles). However, up to 2,000 cycles have been achieved with cell design improvements, heavily derating the discharge capacity and using active charge equalization techniques (see section “[Cell Charge Equalization](#)”).
- One of the major drawbacks is the thermal runaway problem. It can occur due to improper design of battery or charger.

Application Examples Lead-acid batteries are commonly installed in uninterruptible power supply (UPS) systems, in renewable and distributed power systems. Traditionally, they were used as SLI batteries in automobiles. Other applications include telephone systems, power tools, communication devices, emergency lighting systems, and as the power source for mining and material-handling equipment.

Charging Characteristics Lead-acid batteries do not exhibit memory effect. However, it is very vital to have the correct charge and float voltages to achieve a long life. Charging up to the rated voltage level is a must; any deviation from this voltage level leads to electrode corrosion or negative plate sulfation in the long run. Lead-acid batteries used for deep-cycle applications usually have a short life of about 300 discharge/charge cycles.

Lead-acid batteries are typically charged in three stages, which are constant-current bulk charge, equalization final charge, and float charge. The *constant-current charge* provides bulk of the charge and takes up about half of the required charge time. The *equalizing charge* continues charging at a lower charge current and ensures all cells are fully charged and the state-of-charges are similar. This may be done through active techniques or simply overcharging some cells to ensure the undercharged ones receive a full charge. The *float charge* compensates for the self-discharge loss when a battery sits unused for a period of time.

Valve-Regulated Lead Acid (VRLA)

General Characteristics The valve-regulated lead-acid (VRLA) battery is a completely sealed cell, which prevents electrolyte loss due to outgassing, and hence alleviates the need to water the cells. The VRLA battery incorporates the gas recombination principle which allows the oxygen generated at normal overcharge rates to be reduced at the negative plate, eliminating oxygen outgassing. If the rate of outgassing exceeds the rate of recombination, the partial pressure of hydrogen builds up and can cause the vent to open, which destroys the cell.

Advantages and Disadvantages

Advantages include:

- VRLA batteries do not require “watering” as is the case with other types of lead-acid batteries since the water level is maintained due to a regenerative cell reaction. Thus, VRLA batteries do not require the frequent maintenance for battery operation, which is an advantage over the conventional lead-acid battery.
- Battery cells can be packaged more tightly because of sealed construction and immobilized electrolyte, hence the footprint and weight of the battery are reduced.

- SoC is measured by measuring the voltage (The open-circuit voltage can therefore be used to approximate the state of charge). The measurement of the open-circuit voltage to determine the SoC is based on the relationship between the electromotive force and the concentration of the sulfuric acid in the battery.
- One of the major advantages with VRLA batteries is that they do not experience memory effect which is common with nickel cadmium batteries.

Disadvantages include:

- These batteries have a shorter life span than other types of lead-acid batteries. In UPS applications, a life span of 5–10 years is typical since their life reduces due to harsh operating conditions.
- They should not be stored in discharged condition.
- These batteries are sensitive to higher temperature environment. As with most batteries, the capacity is dependent on the discharge rate and temperature; the capacity decreasing with decreasing temperature and increasing discharge rate.
- Electrolytes act as heat sinks in batteries. However, VRLA batteries are “acid starved” as they use much less electrolyte, hence they do not have an effective heat-sink mechanism which makes them more prone to thermal runaway condition than compared to flooded lead-acid batteries.
- They have low cell resistance; hence immense short-circuit current is available.

Application Examples Because the VRLA batteries are sealed, they are ideal for many consumer applications. They are found in many uninterruptable power supply systems for computers, and as backup power for other electronics’ light security systems, and emergency lighting. Because high discharge rates are possible, they are also advantageous for engine starting.

Charging Characteristics Constant-voltage charging is the most efficient and fastest method of charging the VRLA battery. To carry out fast charging of VRLA battery, the charger must be capable of charging the battery at the 2C-rate. Fast charging is usually possible with a full charge achieved within 4 hours, and some batteries that accommodate even higher C-rates can charge so that they are returned to full capacity within

1 h. When float charging is used, the charger maintains each cell at 2.3–2.4V in order to ensure a complete charge and maximum battery life.

Nickel Cadmium (Ni-Cd)

General Characteristics Nickel-cadmium battery is a very reliable, sturdy, long-life battery. Little maintenance is needed on nickel-cadmium batteries. These batteries have two major variants based on the intended application. Cells with thin sintered plates have low internal resistance and have a high power to volume ratio, while cells with thick electrode plates have a high energy storage capacity. Nickel-cadmium batteries are manufactured as unsealed open/semi-open batteries in which electrolyte/gas can escape through a vent (vented Ni-Cd batteries) and as fully sealed batteries which do not require topping up of the electrolyte with water. Nickel-cadmium batteries exhibit voltage suppression, also called as memory effect. The memory effect causes the battery to deliver only the capacity, which was used during the repeated charge/discharge cycles before. Because of this, the whole capacity of Ni-Cd batteries should be used for each discharge cycle to avoid a decrease of the maximum capacity. “Memory effect” makes this battery less suited for applications that don’t allow a complete discharge.

Advantages and Disadvantages

Advantages include:

- They have a longer life than compared to lead-acid batteries.
- Extended operating temperature range compared to lead-acid batteries. This makes them more flexible in heavy duty applications in regard to temperature range.
- Extremely rugged batteries.
- Good charge retention. They can be stored for long periods without significant deterioration of SoC.
- These batteries require less maintenance.

Disadvantages include:

- Cadmium is an environmentally hazardous substance. Hence, disposal of Ni-Cd batteries is a major issue.
- They exhibit strong voltage depression (memory effect) phenomenon. This is a major drawback of Ni-Cd cells.

Application Examples Because of their favorable electrical properties, excellent reliability, low maintenance, rugged design, and long life, nickel-cadmium batteries are used in a large variety of applications. Unsealed Ni-Cd with higher capacity ranges are used in high-energy applications such as traction and large emergency power installations. Industrial nickel-cadmium batteries are used in train lighting and air conditioning for rail cars, emergency and standby systems such as emergency brakes and lighting in mass-transit and subway cars, diesel-engine cranking in locomotives and commuter cars, railroad signaling, communication along tracks, as well as standby power in rail stations and traffic control systems. The nickel-cadmium battery is also used in power-generating stations and power distribution. Sealed Ni-Cd batteries are usually of a low energy storage type (30 Ah). These are extensively used in consumer electronics, domestic markets, and low-energy applications.

Charging Characteristics Constant-voltage charging is the preferred method for unsealed nickel-cadmium batteries.

Nickel-Metal Hydride (Ni-MH)

General Characteristics Nickel-metal hydride (Ni-MH) cells share many of the same characteristics as nickel-cadmium cells and reduce some of the disadvantages. A major difference between nickel-metal hydride and nickel-cadmium cells is that cell reaction of nickel-metal hydride cells is exothermic, and hence, internal temperature of Ni-MH cell rises when it is in operation. On the other hand, nickel-cadmium cells have an endothermic cell reaction.

Advantages and Disadvantages

Advantages include:

- These batteries do not pose environmental hazards like Ni-Cd batteries.
- They possess higher specific energy and energy density than nickel-cadmium cells.
- Bipolar battery pack designs are popular as the energy storage in hybrid vehicles.

Disadvantages include:

- Overcharging leads to serious consequences for the battery; it leads to battery heating which in turn releases hydrogen gas and increases fire hazard. As a result, Ni-MH batteries require complex charging circuitry to ensure overcharging does not take place.
- Complex circuitry for charging implies Ni-MH cells cannot be charged on conventional battery chargers. This necessity contributes to an increased cost for Ni-MH battery.
- Limited service life of about 200–300 cycles if repeatedly discharged at high load currents.
- Higher self-discharge rate than Ni-Cd. Hence, the shelf-life of a fully-charged Ni-MH battery is much shorter. The shelf life is improved by adding chemical additives, which lowers the energy density.
- Memory effect is present but to a much lesser extent than Ni-Cd battery.

Application Examples The nickel-metal hydride battery used to be incorporated in computers, cellular phones, and other consumer electronic applications. In recent years, lithium-ion battery has replaced nickel-metal hydride batteries as it possesses a superior specific energy and energy density.

Charging Characteristics Repeated high load current discharging reduces the service life of nickel-metal hydride batteries to about 200–300 cycles. Ideal discharging of these batteries usually occurs at load currents of 0.2–0.5C. Ni-MH battery suffers from a high self-discharge rate. Self-discharge rates are reduced by adding chemical additives to the cell. However, this results in a trade-off, as chemical additives that slow down the self-discharge rate decrease the energy density of the cell. For a particular make of battery, it has been observed that it loses about 32% of charge if stored for about 80 h.

Lithium Ion (Li-Ion)

General Characteristics Lithium-ion cells are often specified for use in high-performance applications where small size and high performance are of paramount importance. They have higher specific energy and energy density than nickel-metal hydride cells.

High energy density of Li-ion cell also makes it less stable. These cells pose a potential fire hazard if not managed properly.

Advantages and Disadvantages**Advantages include:**

- Li-ion cells have a long cycle life (3,000 cycles at 80% depth of discharge). Hence, they are suited for applications which require a large number of charge-discharge cycles.
- They can operate over a wide temperature range.
- Low self-discharge rate leads to a long shelf life for these batteries.
- Rapid charge capability endears these batteries with consumer electronics applications.
- High energy efficiency. These cells can be up to 94% efficient in terms of energy over a cycle.
- No “memory effect.”
- These batteries do not pose an environmental hazard as they are not made up of toxic materials.
- High energy density (300–400 kWh/m³, 130 kWh/ton).
- One of the salient qualities of Li-ion cells is that they have a very high coulombic efficiency as compared to lead-acid cells. A new Li-ion cell exhibits up to 94% coulombic efficiency as against a lead-acid battery which has only 80% coulombic efficiency.

Disadvantages include:

- Li-ion cells have a moderately high initial cost.
- High energy density of Li-ion cells also gives rise to instability and fire hazard issues. This behavior of Li-ion cells makes it mandatory to have a complex protective circuitry. The battery management systems for Li-ion cell must be able to prevent overcharging of these cells. Overcharging in Li-ion cells leads to thermal runaway and subsequently a fire hazard.
- Venting and thermal runaway may take place when cells are crushed.
- Li-ion batteries composed of series strings of cells require charge equalization modules. Li-ion cells do not support low cost, easy to implement passive cell-balancing schemes.

Application Examples Li-ion batteries are employed in high-performance applications where size and energy are important. They are the preferred choice

for consumer electronics such as laptop computers, cellular telephones, and personal media player where long battery life is required. The suitability for use in military, aerospace, and automobile applications is also being explored.

Charging Characteristics Li-ion cells are fabricated in discharged state and thus must be charged before use. The cells are typically charged using either a constant current (CC) or a constant current-constant voltage (CCCV) with a taper charge regime. Exceeding the maximum voltage is a potential safety hazard and can result in irreversible damage to the battery. At the same time, charging to a lower voltage reduces the capacity of the battery. The construction of these batteries tends to make them susceptible to internal short circuits due to impurities. With the demand for higher energy density, an internal short can lead to catastrophic consequences including the risk of fire. Hence, internal temperature rise of the battery pack needs to be monitored as well as cell voltage. These considerations make it crucial to incorporate special control circuitry for lithium-ion batteries for management of charge and discharge. Although Li-ion cells have a flat voltage profile, it has been established in literature that cell open-circuit voltage provides a good estimate of the state of charge (SoC) ranging from 20% to 100%.

Sodium Sulfur (Na-S)

General Characteristics A sodium-sulfur battery is a type of molten metal battery constructed from sodium (Na) and sulfur (S). This battery has a high energy density, high efficiency of charge/discharge (89–92%), and long cycle life, and is fabricated from inexpensive materials. Sodium sulfur batteries usually have operating temperatures of 300–350°C. They are most prominently found in power grid operations, electric trains, and wind generation operations.

Advantages and Disadvantages

Advantages include:

- These batteries are constructed from inexpensive materials.
- Per unit volume, sodium sulfur batteries deliver three to five times more energy than lead-acid

batteries. They have a high specific energy in the range of 160 kW/h.

- Designed to last 15 years through 2,500 full charge/discharge cycles.
- It has up to 89% cell DC efficiency with no self-discharge.
- Insensitive to ambient temperatures which make it suitable to be housed outdoors.
- Extremely fast charge cycling; it can transit from full charge to full discharge in milliseconds.
- Sodium sulfur battery facilitates remote operation and monitoring along with the added benefit of minimum maintenance.

Disadvantages include:

- These batteries require an elaborate thermal management system to ensure energy efficiency.
- Cells need to be hermetically sealed when operated in corrosive outdoor environments.

Application Examples Sodium-sulfur batteries have operating temperatures of 300–350°C and extensively employ sodium polysulfides which are highly corrosive. These considerations make Na-S batteries suitable for large-scale nonmobile applications such as grid energy storage. Sodium-sulfur batteries have many applications in power systems. They are used to provide additional power during voltage sags. They provide prompt spinning reserves for grid frequency control and reactive power support. Sodium-sulfur batteries also perform admirably in stabilization of wind energy fluctuations by providing the necessary additional power. Na-S batteries are a possible energy storage technology to support renewable energy generation, specifically wind farms and solar generation plants. They are also a better option as against pumped hydroelectric storage schemes. In Europe, motivation is toward implementing Na-S batteries for automotive traction applications.

Lithium-Iron Monosulfide

General Characteristics Practical energy densities of 100 Wh/kg are achieved by secondary lithium-iron monosulfide cells. Lithium-iron sulfide batteries require a thermal management system to maintain optimum operating temperatures. Precise voltage monitoring is needed from the charger. This battery

system requires a thermal management system to maintain the rated operating temperature for the battery and a specialized charger in which careful voltage control is maintained. This battery technology was under active research in the 1970s for electric vehicles. It is yet to be commercialized.

Nickel Zinc (Alkaline Rechargeable System)

General Characteristics The nickel-zinc (zinc/nickel-oxide) battery is an alkaline rechargeable system. Currently the nickel-zinc system is capable of delivering about 50–60 Wh/kg and 80–120 Wh/L depending on the specific design. Nickel-zinc batteries are suited for high discharge rate applications such as a camera flash.

Advantages and Disadvantages

Advantages include:

- Good capacity retention has made it a competitor of silver-zinc and silver-cadmium systems. Fully charged nickel-zinc batteries lose about 20% of their original capacity within a month when left on open-circuit at 25°C. Nickel-zinc batteries can be stored for up to 3 years.
- It has a wide range of temperature tolerance (−39°C to +81°C operating temperature).
- One of the major plus points is that it has a flat discharge voltage profile for a significant portion of the discharge.
- Ni-Zn battery possesses a fast recharge capability.
- It has a sealed maintenance-free design.

Disadvantages include:

- The main stumbling block for the success of Ni-Zn battery technology is that Ni-Zn battery possesses a poor cycle life (up to 150 cycles).
- It has a relatively low volumetric energy density.

Application Examples Nickel-zinc provides a very low-cost option for a long-cycle-life alkaline-rechargeable system. The nickel-zinc system is suited for mobile applications such as electric bicycles, electric scooters, electric and hybrid vehicles, or other deep-cycle applications. Deep-cycle applications for nickel-zinc batteries include trolling motors, electric bicycles and scooters, wheelchairs, golf carts, electric

lawnmowers, electric vehicles, and similar uses. Nickel-zinc batteries have the required discharge-rate capability, high cycle life at deep depths-of-discharge, lightweight rugged construction, and are capable of being stored over the winter months without any maintenance charging.

Charging Characteristics The battery should be protected from excessive overcharge and over discharge. Extreme abuse may reduce battery performance and cycle life or cause a potential safety hazard.

Metal Air

General Characteristics The most popular metal-air battery is the zinc-air electrode battery. Zinc-air secondary batteries are being developed which can store three times as much as lithium-ion batteries but only cost half as much. The intended applications include cell phones, portable consumer electronic items, and electric vehicles. Lithium-air, calcium-air, and magnesium-air batteries have also been studied, but cost and problems such as anode polarization or instability, parasitic corrosion, nonuniform dissolution, safety, and practical handling have so far inhibited the development of commercial products.

Advantages and Disadvantages

Advantages include:

- Zinc-air battery has high energy density. Suitable for electric vehicle technologies.
- Zinc-air cells intake air with CO₂ removed. Earlier, this was seen as a disadvantage. However, deployment of this cell on electric vehicles with a CO₂ filter will lead to drastic reduction in CO₂ emissions. Hence, this cell is being proposed as a likely candidate for automotive applications.
- Zinc-air cells have a flat discharge voltage profile.
- These cells have a long shelf life (dry storage).
- Zinc-air battery has a safe battery chemistry which reduces fire hazards greatly.

Disadvantages include:

- Main difficulty in the development of rechargeable zinc-air battery is the deactivation in performance of air electrode after a few charge/discharge cycles.

- Internal short circuit is a major problem in Zn-Air secondary cells. Internal short circuit usually occurs after several charge/discharge cycles due to zinc dendrite growth through the separator.
- Depending on the discharge rate, the energy capacity of the cell drops drastically.
- Drying out of electrolyte limits shelf life once opened to air.
- Limited operating temperature range.

Application Examples Future applications for rechargeable zinc-air batteries include cell phones and electric vehicles. The high energy density, low-cost constituent materials, and relatively safe cell chemistry are some of the positive application advantages of this battery type. However, more efforts are required to increase the number of charge/discharge cycles of this battery before it becomes practical for commercial use.

Zinc-Bromine

General Characteristics The zinc-bromine battery is a high-energy-density battery. There are no toxic materials in this battery system. Zinc-bromine battery is constructed from low-cost materials; the battery cells are made up of plastic. It provides a viable energy storage option for a variety of generation sources and is ideally suited for applications requiring 2–10 h of energy storage. The energy density of this advanced battery makes it attractive for applications where traditional energy storage batteries, such as lead-acid batteries, are unacceptable due to size and weight restrictions. The zinc-bromine battery is a flow battery. Auxiliary systems are required for circulation and temperature control of the electrolyte. The zinc-bromine battery has a good shelf life. These batteries are more prominent in the high energy range: 10–500 kWh. These battery systems are custom built for specific applications.

Sodium-Beta

General Characteristics Sodium-beta batteries are high-temperature operating systems and hence have high energy density compared to ambient temperature systems.

Advantages and Disadvantages

Advantages include:

- Sodium-beta batteries are characterized by high energy density, lack of required maintenance, and performance independent of ambient temperature.
- They have a potential for low cost (relative to other advanced batteries) and are cheap as raw materials.

Disadvantages include:

- Thermal management is critical. Requires thermally insulated battery enclosure.
- These batteries operate in the region of 160–500°C. Hence, these batteries must not be affected by ambient temperatures.

Application Examples Sodium-beta battery technologies have been developed for use in relatively large-scale energy storage applications (10–1,000 kWh). Sodium-beta batteries can be used at generation facilities for load leveling, spinning reserve, and area regulation. They are also used for line stability and voltage-regulation purposes at distribution facilities. This technology is also suitable for peak demand reduction and power quality maintenance at a customer site. Sodium-beta batteries have also been investigated for their suitability in traction applications since, for a given physical envelope, sodium-beta batteries can provide significantly greater energy (range) at a reduced weight while meeting the vehicle power requirements compared with conventional battery technologies.

Battery Charging Circuits

Battery Charging Techniques

Proper battery charging techniques can significantly improve battery performance and life cycles. Thus, several factors such as fast charging, good quality of charging current, and avoiding under and over charging are considered. In particular, over charging can damage battery's physical components while under charging can reduce its energy capacity. Therefore, an appropriate control technique for charging process should be adopted. Different battery charging techniques are presented in this section. Operating principle of the battery charge controller is discussed for each technique, and the block diagram of the controller is depicted. Depending on the selected charging

technique, output voltage or current of the converter are fed back to the charge controller circuit. Each charging technique has a charging characteristic curve which is defined as the voltage-current trajectory of the battery during the charging period (v_{bat} versus i_{bat}).

Constant-Current Charging (CC) Constant-current charging is the most conventional battery charging technique. In the charging characteristic curve shown in Fig. 2a, the battery current is kept constant while battery voltage increases during charging until it reaches the maximum allowed value (i.e., rated voltage of the battery). Figure 2b shows the voltage and current profiles of the battery during the charging period. When the battery voltage has reached its final value, the charge controller circuit disconnects the battery from the converter to avoid overcharging and consequent battery failure. The voltage profile of the battery during the charging and discharging intervals is not necessarily linear, as shown in Fig. 2b, and depends on the type of the battery.

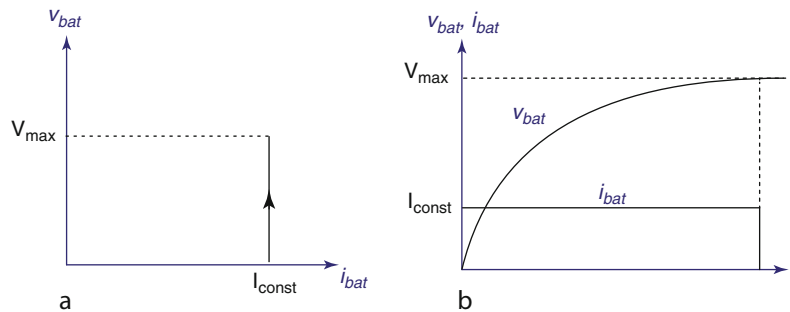
Figure 3 shows the associated control block diagram. The output current is compared with the reference current to produce the error current. The error current is fed to a proportional-integral (PI) controller to eliminate steady state error and generate the command signals for switching of the charger power electronic circuits.

The main advantage of this method is its simplicity. The converter circuit can be realized by an AC-DC or DC-DC converter based on the input type. Moreover, the output capacitor can be dropped as the output voltage regulation is not required, and

regulating merely the output current is sufficient. Elimination of the output capacitor simplifies the converter circuit to a first-order current filter which can be analyzed simply and implemented inexpensively. Fast charging can be realized by large current pumping; however, this has the potential to degrade the internal chemical reactions in the battery. Alternatively, the low charging current prolongs the charging time. Therefore, proper choice of the charging current is crucial for enhancing the charging performance and increasing the lifetime of the battery charging system.

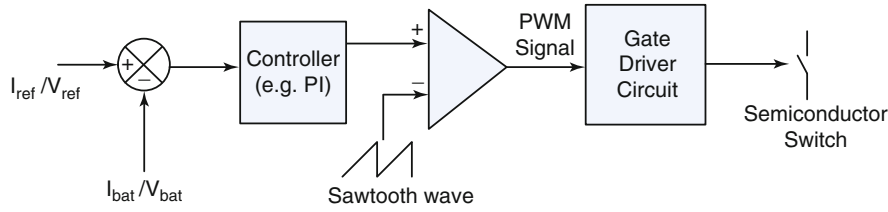
Constant-Voltage Charging (CV) Constant-voltage charging is another conventional battery charging technique. The charging characteristic curve of this technique is illustrated in Fig. 4a. In this method, the battery voltage remains constant while the battery current is decreasing and eventually becomes very low. The current and voltage profile during charging is shown in Fig. 4b. This initial high current (I_o) temporarily increases the battery temperature and can degrade the battery, depending on the chemistry. The battery charge controller disconnects the battery from the charger circuit when the current reaches a specific amount (I_{min}), as shown in Fig. 4b. The control block diagram is shown in Fig. 3, where the sensed and reference variable is the battery and reference voltage, respectively.

Similar to the CC methodology, the CV charging strategy is straightforward and easy to implement. As opposed to the CC charging strategy, a capacitive output is required to regulate the output voltage. This



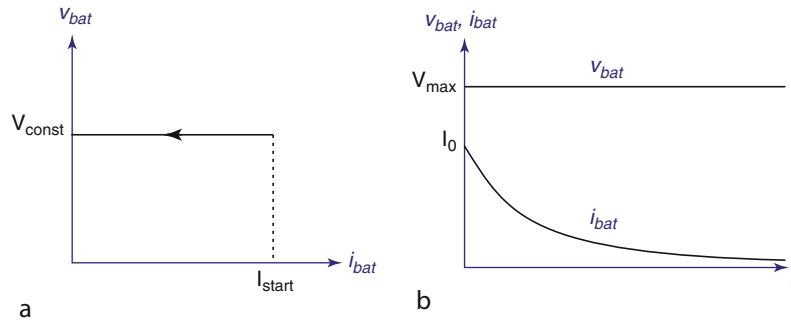
Batteries, Battery Management, and Battery Charging Technology. Figure 2

(a) Charging characteristic curve of the constant-current technique; (b) Current and voltage profiles of the battery during the charging process



Batteries, Battery Management, and Battery Charging Technology. Figure 3

Block diagram of the controller circuit useful for constant-current or voltage charging



Batteries, Battery Management, and Battery Charging Technology. Figure 4

(a) Charging characteristic curve of the constant-voltage technique; (b) Current and voltage profiles of the battery during the charging process

output stage increases the model order, and therefore, the controller design process is slightly more complex than CC technique, yet simple enough for low-cost applications.

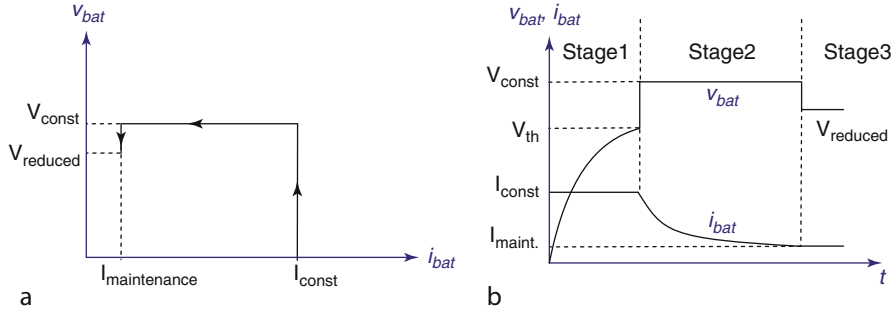
The main disadvantage of the CV charging methodology is the temperature rise of the battery during initial charging stages. While the internal voltage of the battery is very low, the applied voltage at the terminal of the battery is relatively high. Thus, considering the small internal resistance of the battery, a large current will flow which can damage the battery. Another drawback of CV charging is the long charge time due to very low currents at the final stages of the charging.

Mixed Constant-Current and Constant-Voltage Charging (CC-CV) The CC-CV charging technique utilizes both CC and CV charging. Figure 5a, b illustrates the charging characteristic curve and current-voltage profiles of this method, respectively. The charging is performed in three stages. First, the battery current is kept constant until the battery voltage reaches a predetermined value (V_{const}). Then, the

battery voltage is kept constant while the battery current drops below a specific value (I_{min}). The final stage is the float charge stage where the battery voltage is reduced to compensate for the loss caused by self-discharge of the battery.

Since the current is kept constant at the first charging stage, the current rush disadvantage of CV charging technique is avoided. Also, since the voltage is kept constant at the second stage, the overcharging disadvantage of CC charging is avoided. Moreover, the float charging stage keeps the battery in full charge for a long time without degrading the battery. These advantages of CC-CV charging technique make it perfect for applications with high performance requirement. However, the design complexity makes this option more expensive compared to either CC or CV techniques.

Pulse Charging Pulse-charging technique is inherently a CC charging method that uses a pulsating charging current. This pulsating current causes the ions to distribute evenly throughout the battery and electrodes. Consequently, even distribution of ions



Batteries, Battery Management, and Battery Charging Technology. Figure 5

(a) Charging characteristic curve of the CC-CV technique; (b) Current and voltage profiles of the battery during the charging

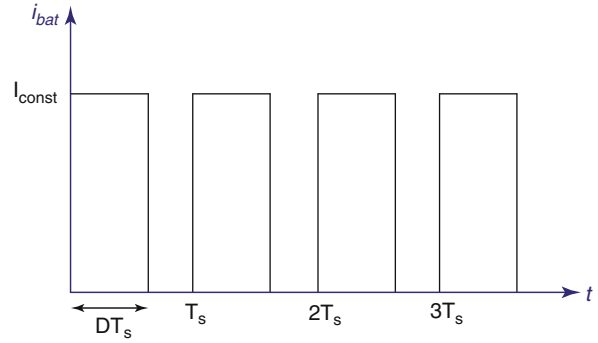
prolongs the lifetime of the battery and enhances the charging performance. Figure 6 shows the current profile of the battery using pulse-charging technique. Due to the internal battery resistance, the battery voltage increases slightly during the charging subintervals. DC value of the charging current can be controlled by the duty cycle of applied current between zero and I_{max} . The charging rate is controlled by the DC value of charging current; thus, charging time of the battery can be controlled by the duty cycle:

$$t_{charge} = f(I_{DC}) = f(DI_{max}), \quad (1)$$

where D , I_{DC} , and I_{max} are the duty cycle, DC value, and the maximum of the battery current, respectively. Large duty cycles are applied during the initial stages of charging to ensure fast charging. After battery voltage is increased sufficiently, the duty cycle gradually decreases to prevent overcharging and consequent battery failure.

Pulse current charging needs an extra control loop to regulate the duty cycle of the reference current (I_{ref}) by the output voltage. As the output voltage decrease, this additional control loop decreases the duty cycle and consequently the DC value of the charging current. Following a pulsating reference current requires a fast control loop. The bandwidth of the control loop should be sufficiently higher than the switching frequency. This bandwidth is limited by the effective bandwidth of the current sensor. Thus, increasing the bandwidth of the controller requires high-bandwidth current sensors, which can be costly.

Taper Characteristic Charging In taper charging, neither battery current nor battery voltage is kept



Batteries, Battery Management, and Battery Charging Technology. Figure 6

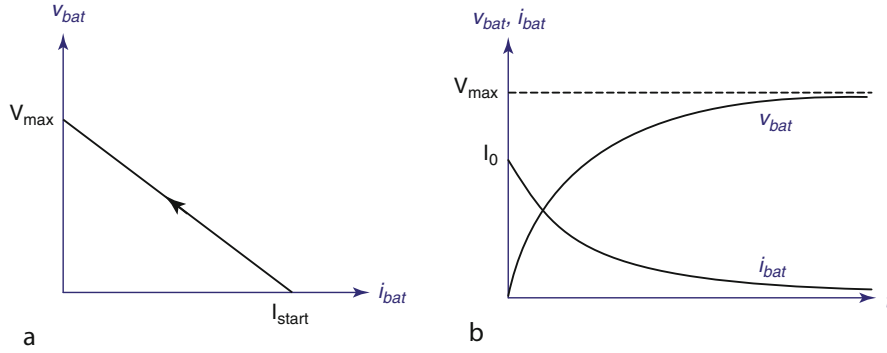
Current profile of the battery using pulse-charging technique

constant. Instead, a linear combination of battery voltage and current is kept constant:

$$k_1 V_{bat} + k_2 I_{bat} = c = \text{constant}, \quad (2)$$

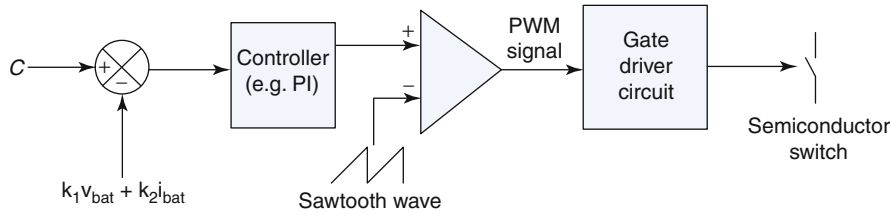
where k_1 and k_2 are constant coefficients which are determined by design requirements. CC and CV charging techniques are special cases of the taper characteristic charging in which $k_1 = 0$ or $k_2 = 0$, respectively. Figure 7a, b illustrates the charging characteristic curve and voltage-current profiles of the taper charging technique, respectively.

The block diagram of the charge controller using this technique is depicted in Fig. 8. Sensing of both battery voltage and current is required and is the main drawback of this strategy. Sensors are usually the most



Batteries, Battery Management, and Battery Charging Technology. Figure 7

(a) Charging characteristic curve of the taper-characteristic-charging technique; (b) Current and voltage profiles of the battery during the charging



Batteries, Battery Management, and Battery Charging Technology. Figure 8

Block diagram of the controller for taper characteristic charging

expensive components of the converter circuits, and increasing the number sensor may drastically increase the total cost of the system.

Assembled Characteristic Charging Assembled or modified charging is a technique whose characteristic curve is a combination of CC, CV, or taper characteristic curves. In this technique, when a certain threshold is reached (e.g., certain voltage), the characteristic curve is changed from one technique to another. Two conventionally assembled characteristic charging methods are assembled constant-current charging and assembled taper characteristic charging.

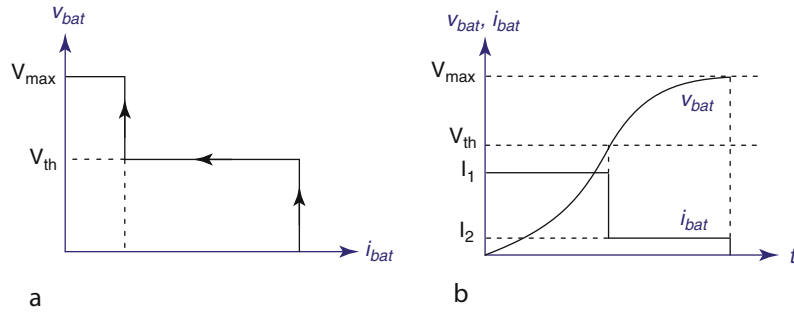
Assembled Constant-Current Charging Figure 9a illustrates the charging characteristic curve of the assembled constant-current charging technique. As seen in Fig. 9a, battery is charged by a high constant current (I_1) until the output voltage reaches the threshold voltage (V_{th}), after which the CC charging will continue using a lower constant current (I_2). Then, charging with low current will continue until the

output voltage reaches its maximum value (V_{max}), which is usually the rated voltage of the battery. The current and voltage profiles of the battery are shown in Fig. 9b.

As the high constant current reduces the charging time but increases the risk of overcharging, one may trade off between fast charging and overcharging protection. This drawback of CC charging has been overcome in assembled constant-current technique. Short charging time can be achieved by using high constant current (I_1) at the first stage ($v \leq V_{th}$), while overcharging can be avoided by using low constant current at the second stage ($v > V_{th}$).

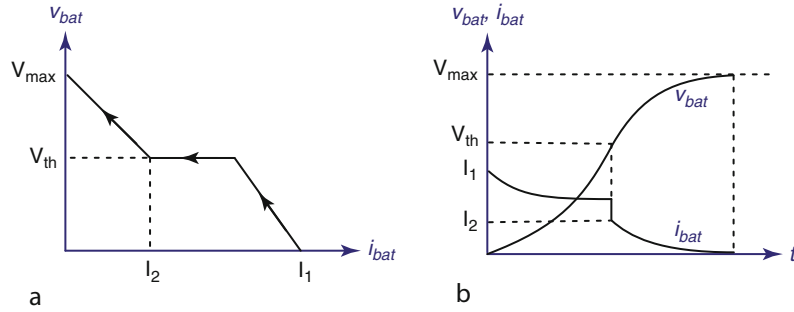
Assembled Taper Characteristic Charging Assembled taper characteristic charging utilizes two different taper charging characteristic curves, as shown in Fig. 10a. The characteristic equation of this technique can be expressed as:

$$\begin{cases} k_1 V_{bat} + k_2 I_{bat} = c, & V_{bat} \leq V_{th} \\ k'_1 V_{bat} + k'_2 I_{bat} = c', & V_{bat} \geq V_{th} \end{cases} \quad (3)$$



Batteries, Battery Management, and Battery Charging Technology. Figure 9

(a) Charging characteristic curve of the modified constant-current technique; (b) Current and voltage profiles of the battery during the charging process



Batteries, Battery Management, and Battery Charging Technology. Figure 10

(a) Charging characteristic curve of the modified taper characteristic technique; (b) Current and voltage profiles of the battery during the charging

where $c > c'$. Figure 10b depicts current and voltage profiles of the battery during the charging time interval.

Enhanced charging performance and prolonged battery life can be achieved using this technique. The main disadvantages of this technique are implementation complexity and using two sensors (current and voltage sensors).

Qualitative Comparison Between Different Charging Techniques Table 1 summarizes different charging techniques and their main properties:

Battery Charging Circuits for Photovoltaic (PV) Systems

Energy storage components are an essential part of a stand-alone photovoltaic (PV) system as they store energy during the high radiation hours during the day

and supply load during the low-radiation hours and nights. The battery is an effective energy storage technology for a PV systems. Lead-acid batteries are common due to their high energy density, prevalence and low cost. Different structures that can be used to connect the battery stack to the PV panel are presented in the next sections. In all of these structures, a series diode is connected between the PV panel and the battery to protect the battery against short circuit during the low-radiation conditions and nights.

Series Charge Regulators Figure 11 illustrates a typical charge regulator structure which can be used for both series and parallel charging. In series charging, switch S_2 is always open. Switch S_1 disconnects the PV panel from the battery when state of charge (SoC) of battery reaches 100% to protect the battery against overcharging. Switch S_3 disconnects the battery from

Batteries, Battery Management, and Battery Charging Technology. Table 1 Qualitative comparison between different charging techniques

Charging technique	Advantages	Disadvantages
Constant current (CC)	<ul style="list-style-type: none"> • Simplicity of implementation • First order open-loop transfer-function • Simplicity of the controller 	<ul style="list-style-type: none"> • Overcharging risk if high charging current is used • Prolonged charging time if low current is used
Constant voltage (CV)	<ul style="list-style-type: none"> • Simplicity of implementation 	<ul style="list-style-type: none"> • Battery temperature rise during the initial stages of charging • Prolonged charging time due to low current during the final charging stages • Second order open-loop transfer-function
Constant current – constant voltage (CC – CV)	<ul style="list-style-type: none"> • Protecting the battery against overcharging • No current rush at the beginning stage of charging • Enables float charging after the battery is fully charged • High performance 	<ul style="list-style-type: none"> • Requires both voltage and current sensor for closed-loop control
Pulse current	<ul style="list-style-type: none"> • Even distribution of ions throughout the electrodes and inside the battery • Prolonged battery life due to maximizing chemical performance • Charging rate can be controlled by the duty cycle of the battery current 	<ul style="list-style-type: none"> • Requires fast control-loop • Requires high bandwidth current-sensor • Expensive
Taper characteristic	<ul style="list-style-type: none"> • Gradual current decrease during the charging • Protection against overcharging 	<ul style="list-style-type: none"> • Requires both voltage and current sensor for closed-loop control • Complexity of implementation
Assembled constant current	<ul style="list-style-type: none"> • Eliminates overcharging property of CC charging • Eliminates prolonged charge time property of CC charging • Takes other advantages of CC charging 	<ul style="list-style-type: none"> • More complicated control scheme than CC charging
Assembled taper characteristic	<ul style="list-style-type: none"> • Different adjustment of characteristic curve is possible to satisfy different design requirements • Enhanced charging performance 	<ul style="list-style-type: none"> • Requires both current and voltage sensors for closed-loop control • Most complex control scheme

the load when the battery SoC is less than a predefined value to avoid deep discharging mode, which can degrade the battery and shorten its life. All switches should have very low loss which means they should have very low forward voltage and on-time resistance. Thus, mechanical relays are preferred to fast power semiconductors such as IGBTs with high on-time voltage drops.

Shunt Charge Regulators In a typical shunt charge regulator, the switch S_1 in Fig. 11 is always closed, and

switch S_3 operation is similar to series charge regulators to disconnect the load from the battery when battery SoC is less than a predefined value to prevent the battery from deep discharging. Switch S_2 shorts the output of the PV panel during low-radiation conditions and nights. When the output of the PV panel is shorted, series diode protects the battery against short circuit condition.

Pulse-Width Modulation Charge Regulators Superior charging functionality can be achieved using

pulse-width modulation (PWM) charge regulators. PWM-type charge regulators are able to eliminate external disturbances and can be programmed to follow a specific charging technique that has been discussed in section “[Battery Charging Techniques](#)”. [Figure 12](#) shows a buck-boost-type PWM charge controller with voltage and current feedback. The charge controller also has the ability to control switch S_2 to

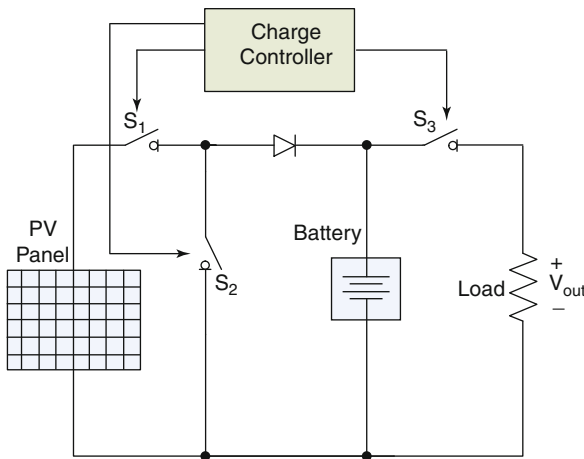
disconnect the load under the condition in which battery SoC is less than a predefined value to protect the battery against deep discharging.

Battery Charging Circuits with AC Sources

Several factors should be considered when designing a charging circuitry with AC input voltage, e.g., nominal output DC voltage, allowable ripple in output current, type of the input AC voltage source (single-phase or three-phase), AC voltage source ratings (voltage and frequency), charger efficiency and power factor, charger current limiting capability, and recharge duration time. In this section, the conventional battery charger's configurations with an AC input source are discussed.

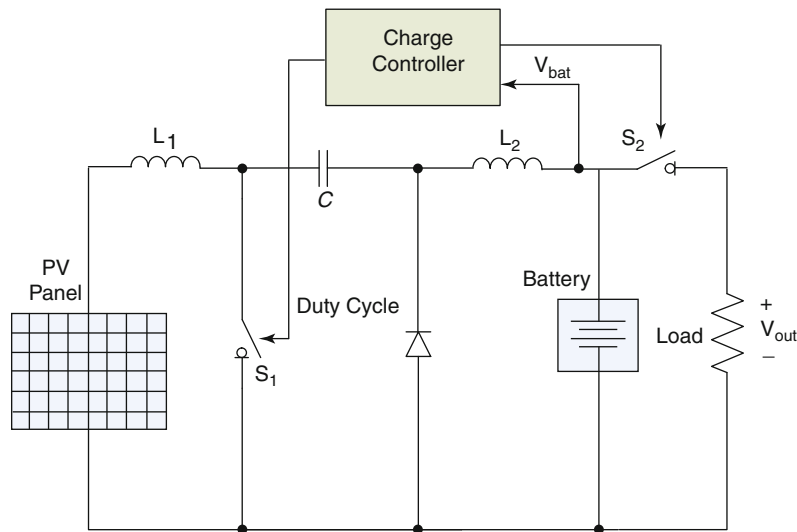
Battery Charger Configurations Given the DC nature of batteries, a rectifier circuit is needed. In a conventional configuration, shown in [Fig. 13](#), a phase-controlled rectifier is adopted. Another configuration is a rectifier bridge in series with a buck DC-DC converter as shown in [Fig. 14](#). If an electrical isolation is required, a DC-DC converter with a high-frequency isolation transformer can be used as shown in [Fig. 15](#).

Single-Phase, Phase-Controlled Rectifiers The circuit configuration of a single-phase thyristor-controlled rectifier is illustrated in [Fig. 16](#). The battery is presented as a DC voltage source in series with



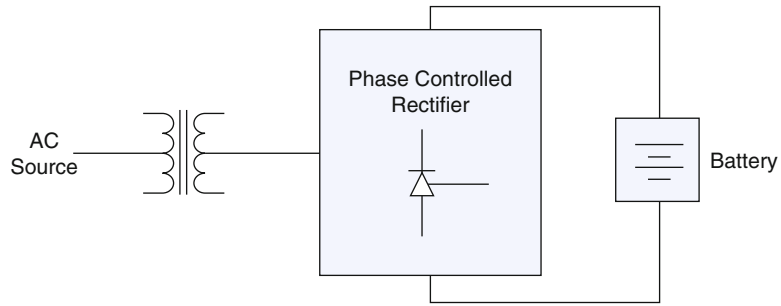
Batteries, Battery Management, and Battery Charging Technology. Figure 11

Circuit diagram of series and shunt PV charging system

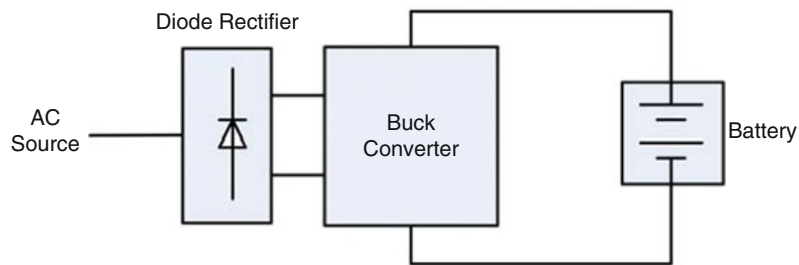


Batteries, Battery Management, and Battery Charging Technology. Figure 12

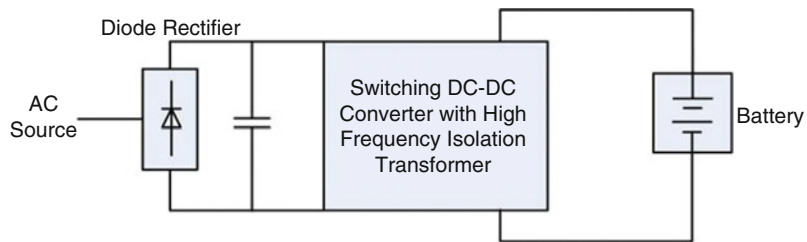
Circuit diagram of the PWM-PV charging system



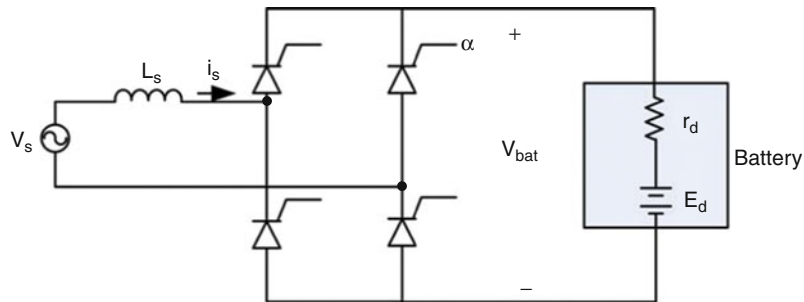
Batteries, Battery Management, and Battery Charging Technology. Figure 13
Phase-controlled rectifier



Batteries, Battery Management, and Battery Charging Technology. Figure 14
Rectifier bridge in cascade with a buck converter



Batteries, Battery Management, and Battery Charging Technology. Figure 15
DC-DC converter with a high-frequency isolation transformer



Batteries, Battery Management, and Battery Charging Technology. Figure 16
Single-phase thyristor rectifier

a resistor (r_d). Considering a continuous battery current, the voltage and current waveforms are illustrated in Fig. 17. Due to the presence of AC side inductance, there is a commutation interval, u . In the continuous mode of battery's current, the approximate average value of the battery voltage is:

$$V_{\text{bat}} \approx 0.9 V_s \cos \alpha - \frac{2}{\pi} \omega L_s I_{\text{bat}, \min} \quad (4)$$

where $I_{\text{bat}, \min}$ is the minimum value of battery current which occurs at $t = \frac{\omega}{\alpha}$.

The average value of battery current can be calculated using (5):

$$V_{\text{bat}} = r_d I_{\text{bat}} + E_d. \quad (5)$$

Figure 18 shows the input line current (i_s). Neglecting L_s , AC source current is a square wave current with only odd harmonics. These harmonics can be expressed as (6):

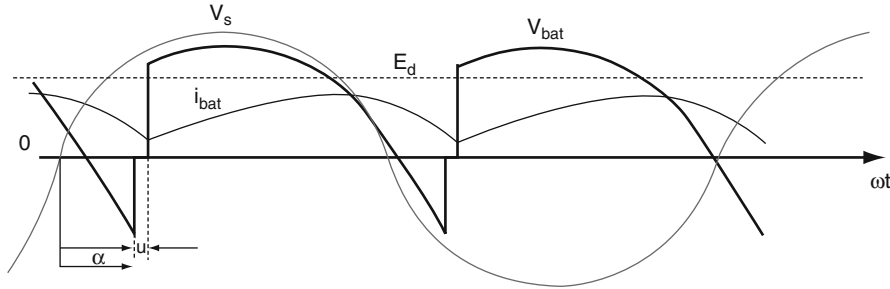
$$I_{\text{sh}} = \frac{I_{s1}}{h} \quad (6)$$

where I_{s1} is the RMS value of the fundamental frequency of I_s . The total harmonic distortion of input line current in a single-phase configuration is around 48.43%. The power factor of the single-phase configuration is expressed in (7):

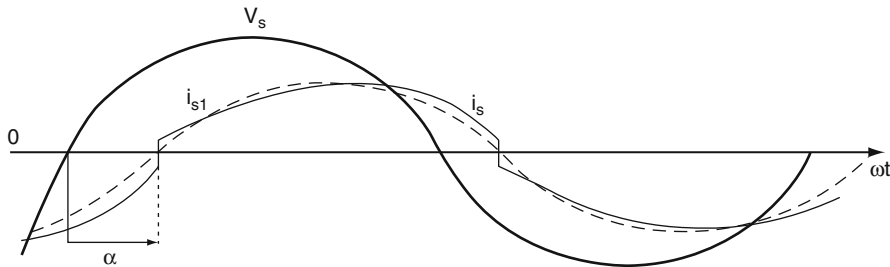
$$PF = 0.9 \cos \alpha. \quad (7)$$

At low values of i_{bat} , the battery current waveform may become discontinuous as shown in Fig. 19. Through the appropriate choice of firing angle α , one can control the average value of battery voltage and thus battery current and, therefore, the power delivered. Figure 20 shows the variations of V_{bat} versus i_{bat} for different values of α . For a given value of α , if i_{bat} becomes less than a specific threshold, V_{bat} increases sharply. In such a case, α has to increase to keep V_{bat} constant.

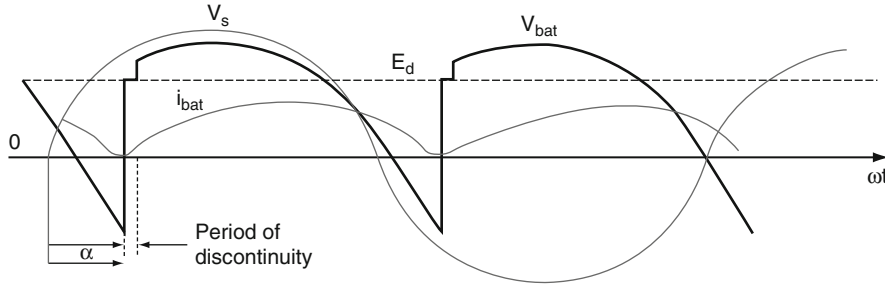
Three-Phase, Phase-Controlled Rectifiers Figure 21 shows the circuit configuration of a three-phase phase-controlled rectifier connected to a battery. Similar to the single-phase configuration, the battery is presented as a DC voltage source in series with a resistor (r_d).



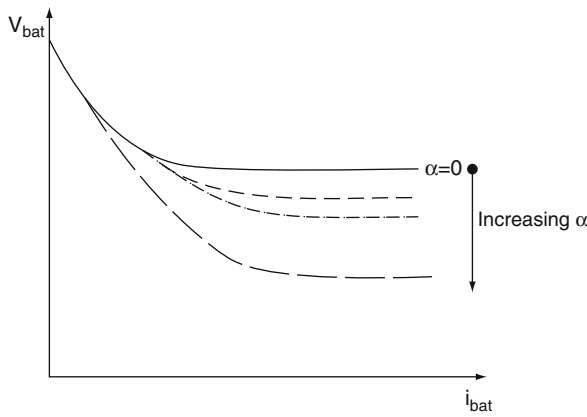
Batteries, Battery Management, and Battery Charging Technology. Figure 17
Battery's voltage and current waveforms



Batteries, Battery Management, and Battery Charging Technology. Figure 18
Input line current



Batteries, Battery Management, and Battery Charging Technology. Figure 19
Battery voltage and current in discontinuous mode of operation



Batteries, Battery Management, and Battery Charging Technology. Figure 20
Rectifier output profile for different values of α

Assuming a continuous current for battery, battery's voltage waveform is illustrated in Fig. 22. In this figure, u and α present the commutation interval and delay angle, respectively. The average value of battery voltage can be expressed in terms of (8). Compared with the single-phase configuration, the ripple in the output voltage of three-phase rectifier is less:

$$V_{bat} \approx \frac{3\sqrt{2}}{\pi} V_{LL} \cos \alpha - \frac{3}{\pi} \omega L_S I_{bat} \quad (8)$$

where V_{LL} is the RMS value of the line voltage of AC source, and I_{bat} is the battery current.

Figure 23 shows the input line current of phase "a" (i_s). Neglecting L_S , AC source current harmonics can be expressed as (9):

$$I_{sh} = \frac{I_{s1}}{h} \quad \text{where } h = 6n \pm 1 \quad (9)$$

The total harmonic distortion of input line current in three-phase configuration is around 31.08%, less than that of a single-phase configuration. The power factor of three-phase configuration is:

$$PF = \frac{3}{\pi} \cos \alpha. \quad (10)$$

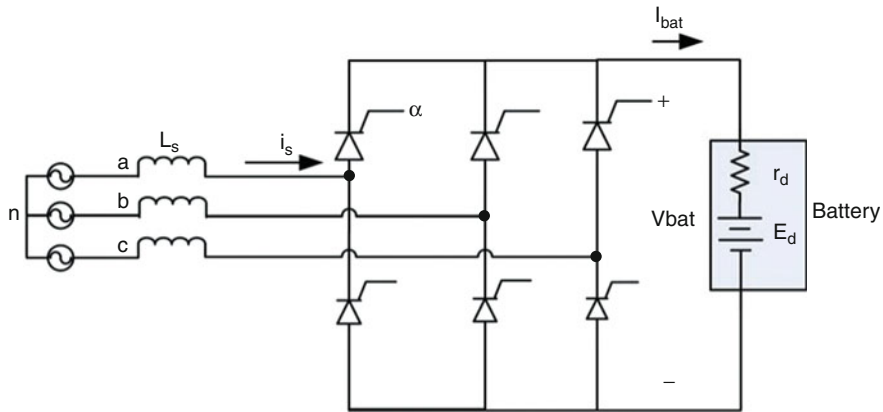
Rectifier Bridge in Cascade with a Buck DC-DC Converter In this configuration a rectifier is in cascade with a buck DC-DC converter. In the buck converter, which is shown in Fig. 24, the average output voltage is lower than DC input voltage. Figure 25 shows the waveforms of V_d , V_{bat} , V_L , and i_L for a resistive load and continuous conduction of inductor. t_{on} denotes the time that the switch is on in a switching period. Because of the fact that the integral of the inductor voltage should be zero over a time period, the output voltage is:

$$\frac{V_{bat}}{V_{in}} = \frac{t_{on}}{T_s} = D. \quad (11)$$

Ignoring losses, the expression for output current is:

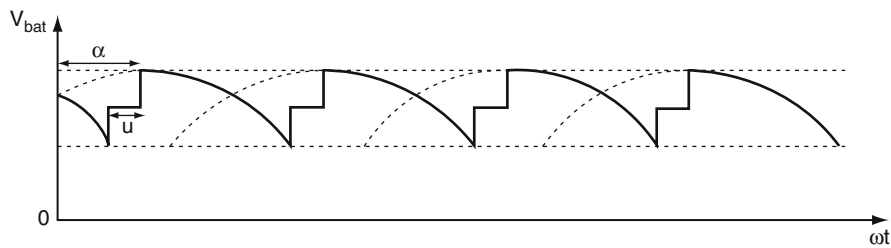
$$\frac{I_{bat}}{I_{in}} = \frac{V_{in}}{V_{bat}} = \frac{1}{D}. \quad (12)$$

DC-DC Converter with a High Frequency Isolation Transformer In this configuration using a diode rectifier, the input AC voltage is rectified into a primary DC voltage. Using high-frequency switching, the primary DC voltage is converted from one DC level to another. This task is done by using a high-frequency transformer. The output of this configuration is controlled by adopting a PWM feedback control. Figure 26 shows the simplified block diagram of this configuration with its control system. Flyback, forward,



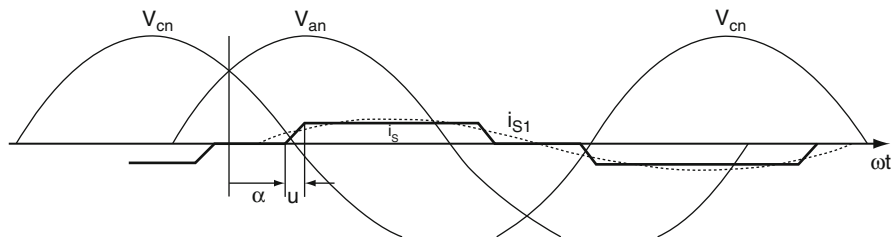
Batteries, Battery Management, and Battery Charging Technology. Figure 21

Three-phase phase-controlled rectifier



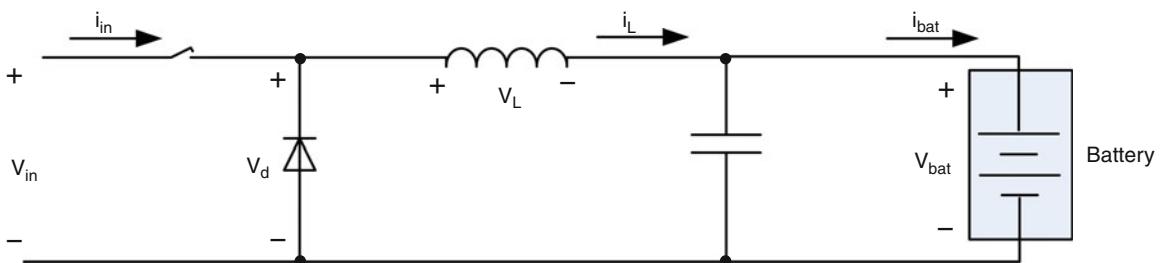
Batteries, Battery Management, and Battery Charging Technology. Figure 22

Battery's voltage waveform



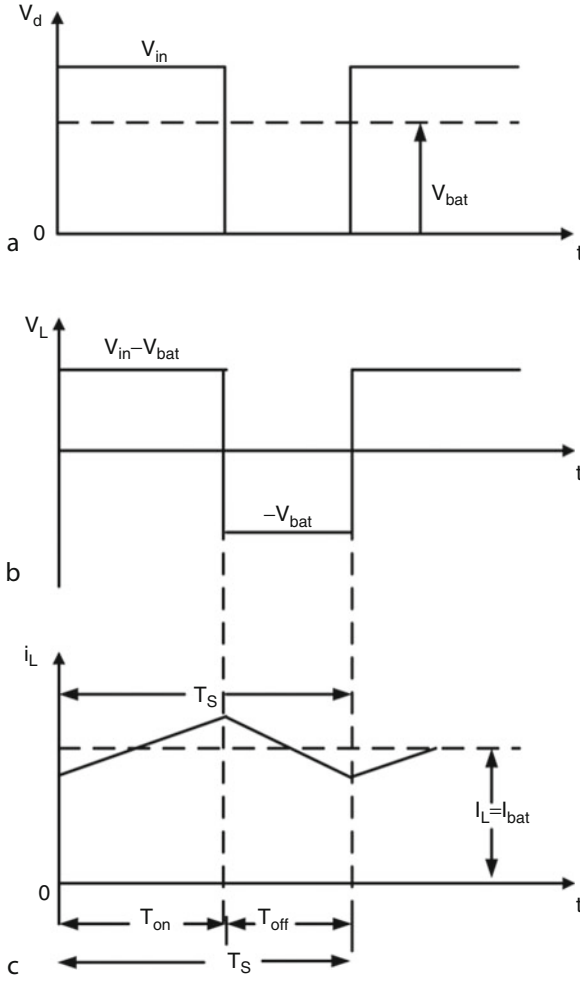
Batteries, Battery Management, and Battery Charging Technology. Figure 23

Input line current



Batteries, Battery Management, and Battery Charging Technology. Figure 24

Buck converter



Batteries, Battery Management, and Battery Charging Technology. Figure 25

(a) Diode voltage; (b) Inductance voltage; (c) Inductance current

push-pull, half bridge, and full bridge are the main types of this battery configuration.

Flyback Converter Figure 27 shows the circuit topology of this converter. This converter is derived from buck-boost converter. Defining the switch duty ratio D as the ratio of the time the switch is on t_{on} to the total switching period T_s , $D = \frac{t_{on}}{T_s}$, the DC output voltage is:

$$\frac{V_{bat}}{V_{in}} = \frac{N_2}{N_1} \frac{D}{1-D}. \quad (13)$$

Forward Converter Figure 28 shows the circuit topology of this converter. This converter is derived

from a step-down (buck) converter. The expression for the DC output voltage level is:

$$\frac{V_{bat}}{V_{in}} = \frac{N_2}{N_1} D. \quad (14)$$

Push-Pull Converter Similar to forward converters, push-pull converters also have the same operation as buck converters. Circuit configuration of these converters is shown in Fig. 29. The expression for the DC output voltage level is:

$$\frac{V_{bat}}{V_{in}} = 2 \frac{N_2}{N_1} D, \quad 0 < D < 0.5. \quad (15)$$

In practice, in order to avoid simultaneous conduction of both switches, D should be less than 0.5.

Half-Bridge Converter Figure 30 shows the circuit configuration of this converter. This converter is also derived from step-down converters. The expression for the DC output voltage level is:

$$\frac{V_{bat}}{V_{in}} = \frac{N_2}{N_1} D, \quad 0 < D < 0.5. \quad (16)$$

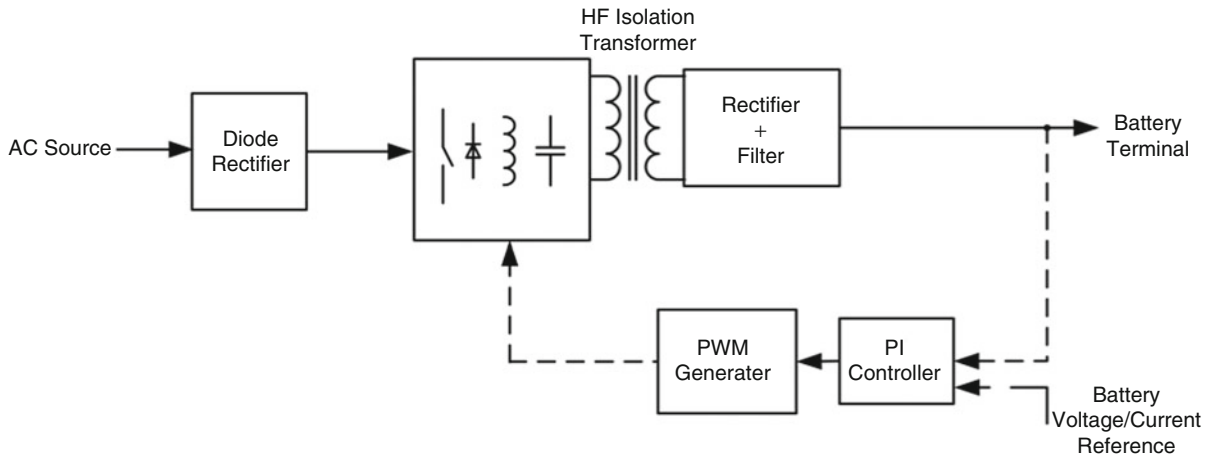
Full-Bridge Converter Full-bridge converters also have the same operation as buck converters. Their circuit configuration is shown in Fig. 31. The expression for the DC output voltage level is:

$$\frac{V_{bat}}{V_{in}} = 2 \frac{N_2}{N_1} D, \quad 0 < D < 0.5. \quad (17)$$

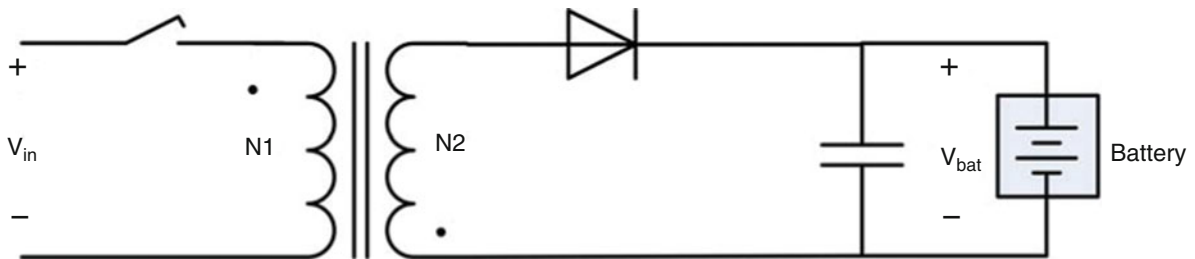
Bidirectional Configurations for Battery Charging with AC Sources

Bidirectional configurations for battery charging are used in multifunctional battery energy storage systems (BESS) and plug-in hybrid electric vehicles (PHEV). In the case of BESS, considering normal operation of the power system, the battery package can be charged and BESS can be controlled to shave the pick load. In the power failure condition, the battery pack is discharged and BESS provides an uninterruptible power for the utility grid. Figure 32 shows a three-phase configuration of a BESS system. Sophisticated control systems provide required commands for the switching system of the bidirectional converter which is a current-forced sinusoidal pulse-width modulated switching.

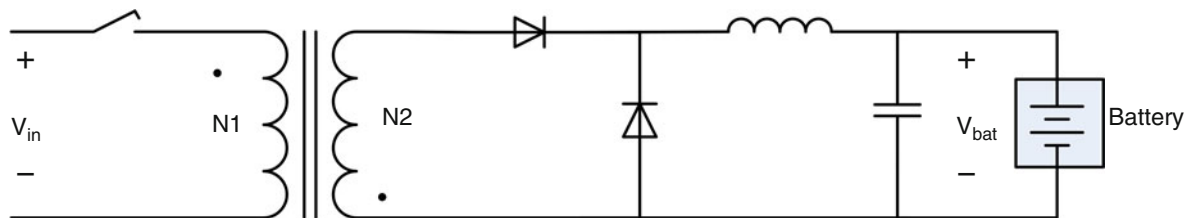
In the case of PHEVs, the battery pack should have this capability to store energy from an external power



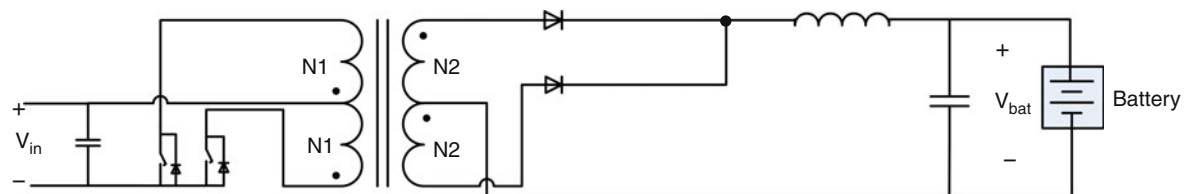
Batteries, Battery Management, and Battery Charging Technology. Figure 26
DC-DC converter with a high-frequency isolation transformer and its control system



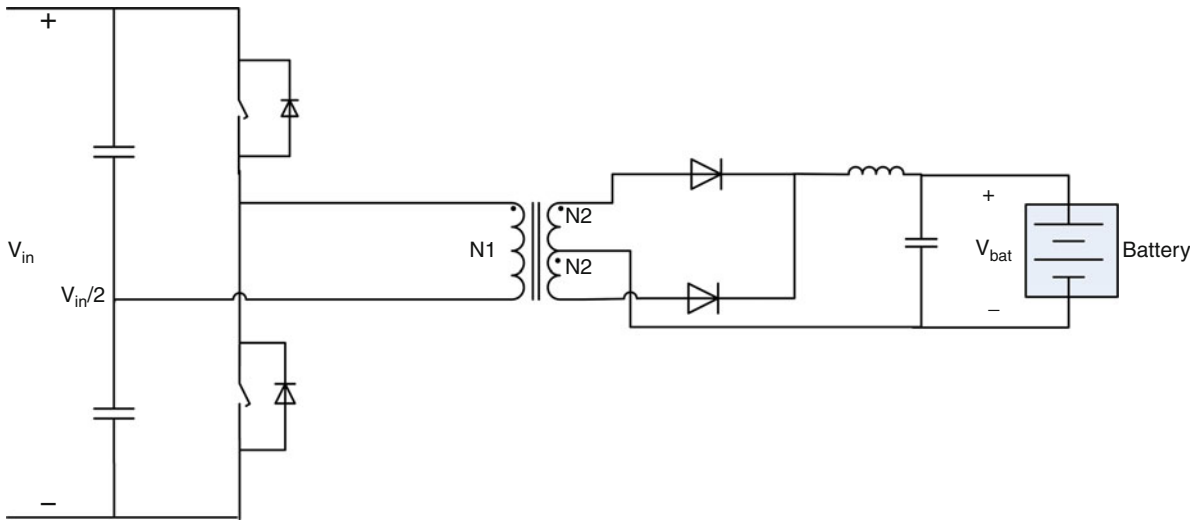
Batteries, Battery Management, and Battery Charging Technology. Figure 27
Flyback converter



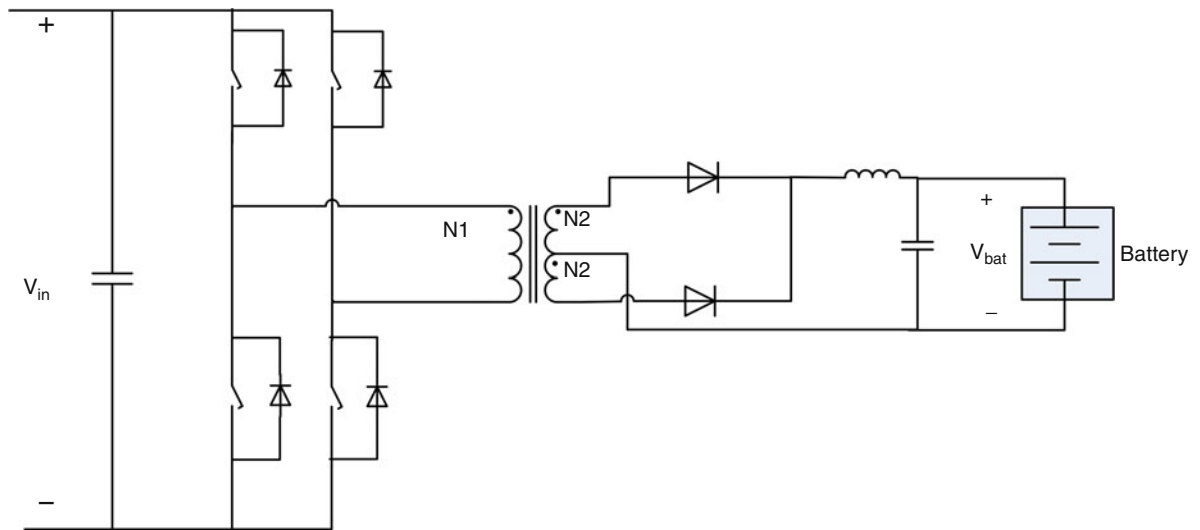
Batteries, Battery Management, and Battery Charging Technology. Figure 28
Forward converter



Batteries, Battery Management, and Battery Charging Technology. Figure 29
Push-pull converter



Batteries, Battery Management, and Battery Charging Technology. Figure 30
Half-bridge converter



Batteries, Battery Management, and Battery Charging Technology. Figure 31
Full-bridge converter

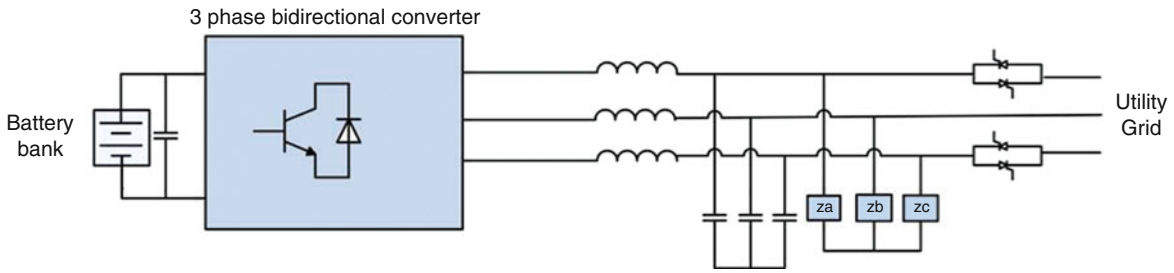
source and regenerative braking as well as sending back the stored energy to the utility grid. Figure 33 shows the PHEV battery charger configuration. This battery charger consists of a bidirectional AC-DC converter in cascade with a bidirectional DC-DC converter.

Contactless Battery Charging

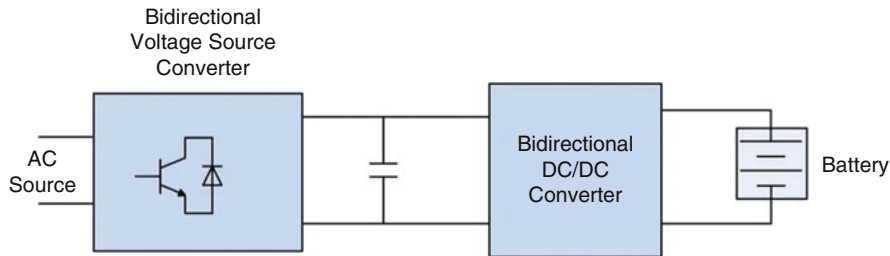
In recent years, a new approach for battery charging, named contactless battery charging, has emerged. This

new charging scheme alleviates the wiring requirements and provides an easy charging process for cell phones, laptops, cameras, PHEVs, etc. Currently, there are two dominant technologies for contactless battery charging named inductive contactless battery charging and capacitive contactless battery charging.

Inductive Contactless Battery Charging The planar contactless battery charging platform is the



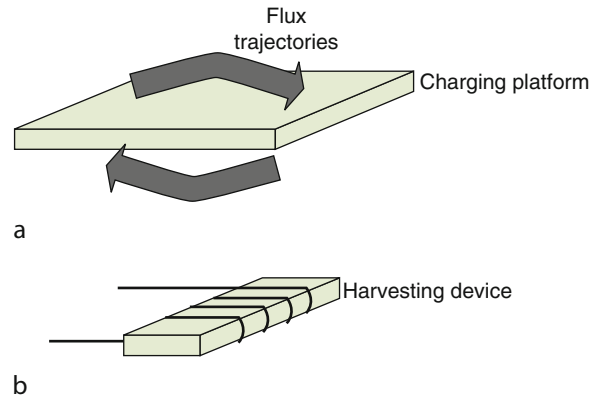
Batteries, Battery Management, and Battery Charging Technology. Figure 32
Bidirectional configuration for BESS



Batteries, Battery Management, and Battery Charging Technology. Figure 33
Bidirectional configuration for PHEV

predominant technology for contactless chargers. It uses inductive interface between energy transmitter and energy receiver and has the potential to unify all battery charging protocols related to portable electronic devices such as cell phones, music players, etc. Generally, there are two main schemes for implementing inductive contactless battery charging. The first scheme adopts horizontal flux in which magnetic flux moves horizontally onto the planar charging surface and flows on both sides of the planar. To achieve this requirement, a thick layer of soft magnetic material such as ferrite or amorphous alloy as the flux guide is used. Figure 34a shows the charging platform with horizontal magnetic flux trajectories. Figure 34b shows the secondary harvesting device which should pick up the fluxes from the surface of the charging platform. This energy-harvesting device consists of a magnetic core and a winding and is mounted into the portable electronic device. The cross-sectional area of this device should be large enough to collect enough flux and energy.

The second scheme adopts perpendicular flux in which magnetic flux has a perpendicular trajectory



Batteries, Battery Management, and Battery Charging Technology. Figure 34

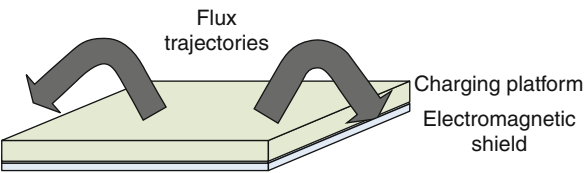
(a) Charging platform with horizontal magnetic flux trajectories; (b) Energy-harvesting device

flow to the charging platform surface. The magnetic flux has uniform magnitude over the charging platform. This perpendicular flux trajectory allows a slim energy harvester device which is mounted into the portable electronic device. Figure 35 shows the

charging platform with perpendicular magnetic flux trajectories.

Figure 36 shows the block diagram of an inductive contactless charger. The harvested energy is rectified, limited, and regulated to generate a DC voltage across the battery's terminals. Under and over discharge protection, setting of the battery voltage and current profiles, and implementing battery charging control techniques can be achieved by using an appropriate control system. Conventional configurations for battery charging circuits, explained before, can be used for the battery charger.

Capacitive Contactless Charger Thick electromagnetic flux guide is an important requirement in implementing efficient inductive contactless chargers. The confined electric field between conductive plates can alleviate this requirement in capacitive contactless chargers, as shown in Fig. 37. Figure 38 shows the circuit configuration of a capacitive contactless charger based on a series resonant architecture. Two coupling capacitors transfer power from V_{in} to battery. Considering a DC power supply, using an inverter, the input DC voltage is converted to an AC output voltage to enable current flow through the coupling capacitors. This inverter is not required if supplied from an AC

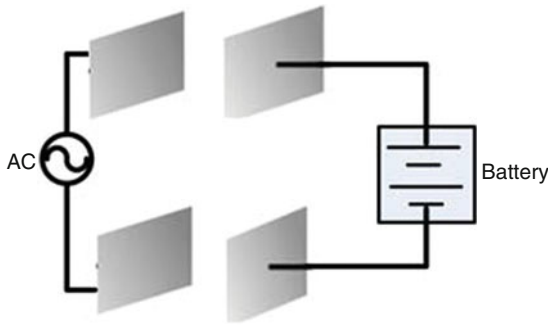


Batteries, Battery Management, and Battery Charging Technology. Figure 35
Charging platform with perpendicular magnetic flux trajectories

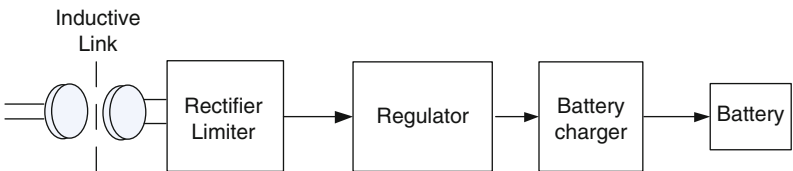
source. Inductors are used to enable soft switching. At the final stage, a diode rectifier provides the required DC voltage for battery charging. The circuit parameters should be designed in such a way that a circuit with the least possible value of capacitor and the desired efficiency is achieved.

Electromagnetic Interference (EMI)

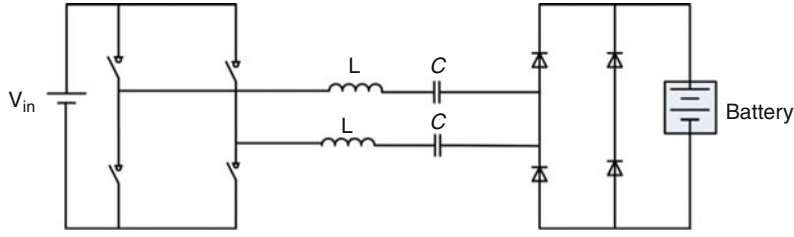
Electromagnetic interference (EMI) is defined as degradation in performance of an electronic system caused by electromagnetic disturbances. Electromagnetic compatibility (EMC) is the ability of that system to operate satisfactorily in an electromagnetic environment without introducing intolerable electromagnetic disturbances to other devices in that environment. Battery charging circuits are power electronic converters in nature. Therefore, EMC rules and regulations exist that apply to the battery charger circuits. Power electronic converters must emit electromagnetic disturbances below the maximum permitted amount (emission) and be able to operate properly when exposed to electromagnetic disturbances below the maximum permitted amount (susceptibility).



Batteries, Battery Management, and Battery Charging Technology. Figure 37
Capacitive contactless power transferring



Batteries, Battery Management, and Battery Charging Technology. Figure 36
Inductive contactless charger scheme



Batteries, Battery Management, and Battery Charging Technology. Figure 38
Capacitive contactless charger circuit configuration

There are four types of electromagnetic disturbances: conductive noise, inductive coupling, capacitive coupling, and radiation.

Conductive Noise Conductive noise addresses disturbances introduced by coupling of two or more circuits through interconnecting wires. For example, when a utility transformer supplies a rectifier, it is exposed to the same current as of the rectifier. Therefore, if the input current of the rectifier has harmonic content that is intolerable for the transformer, it can cause the transformer to malfunction.

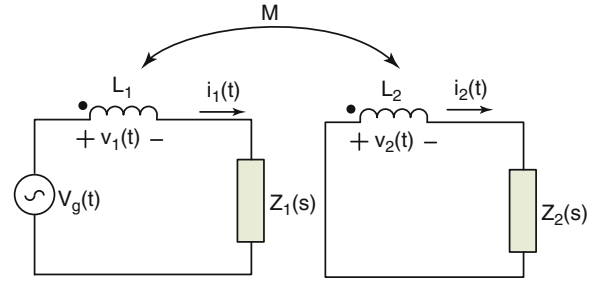
Inductive Coupling Inductive coupling refers to disturbances that are caused by unwanted coupling of windings in different circuits. Leaking flux of an inductor inside a circuit may encircle a winding or a closed path in another circuit and results in inductive coupling. Figure 39 illustrates the modeling circuit of inductive coupling. Mutual inductance, M , indicates the degree to which two circuits are coupled. The winding voltage set is denoted in (18):

$$\begin{cases} v_1 = L_1 \frac{di_1}{dt} + M \frac{di_2}{dt} \\ v_2 = M \frac{di_1}{dt} + L_2 \frac{di_2}{dt} \end{cases} \quad (18)$$

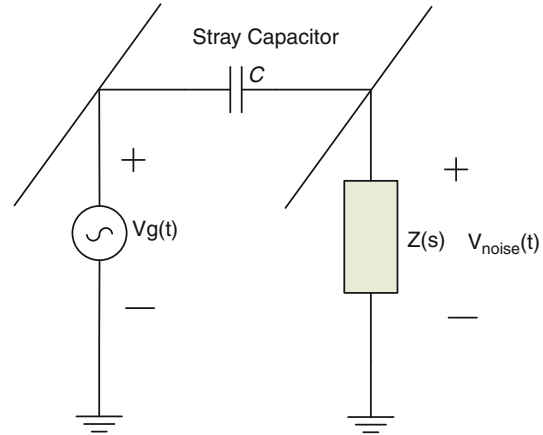
The noise is represented as a mutual term using the mutual inductance

$$v_{\text{noise},12} = M \frac{di_2}{dt}. \quad (19)$$

Capacitive Coupling Figure 40 portrays the capacitive coupling circuit. Capacitive coupling happens when there is a small capacitance between different parts of different circuits, and the medium is electric field. The disturbance voltage caused by V_g can be expressed as:



Batteries, Battery Management, and Battery Charging Technology. Figure 39
Modeling circuit of inductive coupling



Batteries, Battery Management, and Battery Charging Technology. Figure 40
Modeling circuit of capacitive coupling

$$V_{\text{noise}}(s) = \frac{Z(s)Cs}{Z(s)Cs + 1} V_g(s). \quad (20)$$

Thus, decreasing C reduces the magnitude of induced noise voltage.

Radiation Radiation disturbance is caused by the absorption of electromagnetic waves where it is not intended. When the circuit dimensions are very small compared to one fourth of the wavelength of an electromagnetic wave, that electromagnetic wave cannot be fully absorbed by the circuit. Thus, radiation disturbance usually occurs in high-frequency waves with shorter wavelengths.

EMC in Battery Charging Circuits

Different guidelines should be followed in battery charging circuits to reduce electromagnetic susceptibility and emission of the converter circuit. Radiation disturbance is trivial in power electronic converters because switching frequency is relatively low, which means that the wavelength of the electromagnetic wave is much longer than the circuit dimensions. Susceptibility of the converter to capacitive and inductive noises can be diminished by shielding the converter. Air core inductors should be avoided in the converter circuit to meet electromagnetic interference (EMI) and electromagnetic compatibility (EMC) emission requirements. Using air core inductors causes long flux paths through the air that can encircle other windings and cause inductive coupling. On the other hand, using magnetic core inductors defines a specific path for flux through the core and prevents inductive coupling. The most challenging EMC issue of the power electronic converters is conductive noises. As discussed in the previous sections, battery charging circuits are mainly AC-DC or DC-DC circuits. In DC-DC battery charging circuits, pulsating input current should be prevented to meet EMC emission requirements. Thus, buck and buck-boost converters are not suitable candidates. As an alternative, Boost, Ćuk, and SEPIC converters can be used as they have built-in input current filters. The most suitable choice is a Ćuk converter as it has output current filter that makes it perfect for constant-current charging applications. There are two types of AC-DC battery charging circuits, namely phase-controlled rectifiers and PWM rectifiers. Phase-controlled rectifiers draw square shape input currents that have a very high harmonic content. Thus, the designed input current filter for phase-controlled rectifiers should have lower cutoff frequencies which requires larger and bulkier filter components. On the

other hand, the input current of PWM rectifiers has less harmonic content that are located at higher frequencies. This characteristic of the PWM converters enables one to design input current filters by smaller inductors.

Regulations and Standards

Several standards have been developed by different institutes to regulate electromagnetic emission and susceptibility of electrical equipment, namely: MIL-STD 461; IEEE/ANSI SA-C63.14; IEEE 519, IEC 555-2, FCC, title 47, part 15; German VDE; and Japanese standards.

MIL-STD 461 establishes requirements for control of EMI emission and susceptibility of electronic and electromechanical equipment which are produced for use by agencies of the Department of Defense.

IEEE/ANSI SA-C63.14 provides the definitions for specific terms that are related to EMC, electromagnetic pulse (EMP), and electrostatic discharge (ESD).

IEEE-519 regulates the injection of harmonic currents to the power system due to nonlinear loads such as static power converters, arc discharge devices, saturated magnetic devices, and, to a lesser degree, rotating machines.

The IEC 555-2, IEC 1000-3-2, and IEC 1000-3-4 are emission standard related to operation of power electronic converter. These standards usually set an upper limit for harmonic content in each frequency.

Battery Management

Need for Battery Management

Two critical parameters for battery performance are battery voltage and operating temperature. A battery usually consists of a pack of cells connected in series. Manufacturing processes lead to imperfections in cells, as a result of which, all the cells in a pack are not identical. Electrical imbalances occur during charging and discharging of battery packs. Some cells in a battery will have different voltage levels for the same charging. This mismatch needs to be monitored to improve efficiency and safety of battery pack. Higher than rated temperatures in the batteries lead to undesirable chemical effects. Self-sustaining internal temperature buildup and gas pressure buildup are common. These conditions lead to safety hazards. It is vital to have a mechanism to monitor cell temperature and voltage and keep them within limits.

The main role of battery management systems (BMS) is to monitor cell voltage/current, state of charge/state of health, and the internal battery temperature and ambient temperature. The monitoring circuitry provides signals to the protection unit as well. Battery management systems differ on the basis of their primary functions, which depend upon the intended application. BMS for standby batteries in a power plant deal with monitoring of various battery parameters, maintaining readiness to deliver full power in the event of a system failure, and ensuring equal charging to increase battery life. On the other hand, a BMS in an electric vehicle must communicate with other controls in the automobile such as temperature controls, engine management, and safety systems.

There are three main objectives common to all battery management systems:

- Protect the cells or the battery from damage.
- Prolong battery life via smart control.
- Maintain battery in a state in which it can fulfill the functional requirements of the application for which it was specified.

State of Health Measurement

The state of health is a “measurement” that reflects the general condition of a battery and its ability to deliver the specified performance compared with a fresh battery. It takes into account such factors as charge acceptance, internal resistance, voltage, and self-discharge.

It is an estimate rather than a measurement. Battery manufacturers do not specify the SoH because they only supply new batteries. The SoH only applies to batteries after they have started their aging process either on the shelf or once they have entered service. The SoH definitions are therefore specified by test equipment manufacturers or by the user.

Any parameter which changes significantly with age, such as cell impedance or conductance, can be used as a basis for providing an indication of the SoH of the cell. Changes to these parameters will normally signify that other changes have occurred which may be of more importance to the user. These could be changes to the external battery performance such as the loss of rated capacity or increased temperature rise during operation, or internal changes such as corrosion.

Methods of Determining the State of Charge

State of charge (SoC) is defined as the capacity left in a battery expressed as a percentage of some reference. SoC of a battery is usually expressed as a percentage of the current battery capacity when it is fully charged. This definition may lead to an erroneous result when applied to a battery that has been in service for a long time. The maximum capacity of a battery reduces significantly with prolonged use. Considering this value to be the reference for state of charge measurement can lead to false results.

There are several techniques to determine SoC. A majority of them depend on measuring some convenient parameter which varies with the state of charge. Some are specific to particular cell chemistry. Some of the important ones are listed below:

Specific Gravity Measurement In lead-acid batteries, the electrolyte (sulfuric acid) is used up as the battery is subjected to a discharge cycle. As more and more electrolyte is used up, the specific density of sulfuric acid reduces. Thus, the specific gravity of the sulfuric acid is an indication of the state of charge for lead-acid batteries. This method is not feasible for VRLA batteries.

Voltage Measurement Cell voltage typically decreases for most cells during a discharge cycle. There is an almost linear relation between the state of charge and cell terminal voltage. Results may vary depending upon cell terminal voltage, temperature, discharge rate, and age of cell. A compensation factor needs to be included for SoC calculation by this method.

Li-ion cells have a flat voltage profile during a discharge cycle. The cell voltage drops abruptly when they are close to a complete discharge. As the cell voltage variation with SoC is not linear, cell voltage cannot be selected as a parameter to indicate SoC of Li-ion cells. In general, the voltage measurement technique fails for cells which have a flat voltage profile during a discharge cycle.

Current-Based SoC Estimation Charge in or out of the cell is calculated by integrating the current delivered by the cell for certain duration. This charge is

compared with the charge contained by a fully charged cell. This method provides a high accuracy for SoC measurement as it measures the charge directly. Three popular current sensing methods are used.

- **Current shunt:** The simplest method of determining discharge current is by measuring the voltage drop across a low ohmic value, high precision, series, sensing resistor. This resistor, connected between the battery and the load, is called a current shunt. This method of measuring current causes a slight power loss in the current path and also heats up the battery and is inaccurate for low currents.
- **Hall-effect transducers:** The Hall-effect transducers avoid the power loss problem, but they are more expensive. Unfortunately, they do not tolerate high currents and are susceptible to noise.
- **Giant magneto resistance (GMR) sensors:** These sensors are even more expensive than Hall-effect transducers, but they have higher sensitivity. They also have better high temperature stability than Hall-effect devices.

Kalman Filter Technique A Kalman filter is an algorithm to estimate the inner states of any dynamic system. The cell is represented by a mathematical state-space model, and SoC is considered as a state of the system. The Kalman filter accurately estimates the value of SoC and uncertainty. Armed with this information, the battery pack can be subjected to a more complete use, without fear of over- or under-charging cells. Nonlinear models of cells provide a highly accurate result.

The Kalman filter model for a rechargeable battery used in automobiles is initialized with a priori state estimate when the vehicle is turned on. The priori state estimate is provided on the basis of open-circuit voltage readings and a look-up table, self-discharge rate data from the cell model and the prior SoC when the vehicle was turned off. The algorithm then repeatedly updates the state estimate and state-uncertainty (error bound) estimate with each set of new measurements, as the system runs. Laboratory tests on real cells have shown that excellent SoC estimation with very tight error bounds are obtained whether or not the initial SoC estimate is accurate.

SoC Estimation from Internal Impedance Measurements During charge-discharge cycles, the composition of active chemicals changes in the battery, and this is reflected in the changes to internal impedance of the battery. Plots for variation of internal cell impedance with state of charge may be obtained for different cells. Thus, measuring internal impedance can indirectly provide information about SoC of the cell. However, on the flip side, cell internal impedance is also affected by temperature, which may lead to erroneous measurements.

Cell Balancing

When a battery pack is charged and discharged as a unit, individual cell temperature and internal chemistry characteristics can cause capacity imbalances in the form of voltage variations. Imbalances in cell voltages are caused by differences in cell capacities, internal resistances, chemical degradation, and inter-cell and ambient temperatures during charging and discharging. Any capacity imbalance between the modules can threaten the long-term reliability of the string as overall pack capacity is brought to the upper and lower limits of charge. Imbalances in cell voltages can cause cell overcharging and discharging, decreasing the total storage capacity and lifetime of the unit.

In a battery pack consisting of series connected cells, some cells have a diminished capacity owing to slight differences in manufacturing. When such a battery is subjected to charging cycle, the reduced capacity cells reach full charge earlier than the other cells in the battery, and there is a danger of overcharging these degraded cells. The capacity of the anomalous cells reduces even further with every successive charge/discharge cycle. The cumulative result is a temperature and pressure buildup which paves the way for an early failure of the cell.

Once a cell has failed, the entire battery must be replaced, and the consequences are extremely costly. Replacing individual failed cells does not solve the problem since the characteristics of a fresh cell would be quite different from the aged cells in the chain, and failure would soon occur once more. Some degree of refurbishment is possible by cannibalizing batteries of similar age and usage, but it can never achieve the level of cell matching and reliability that is possible with new cells.

Cell Charge Equalization

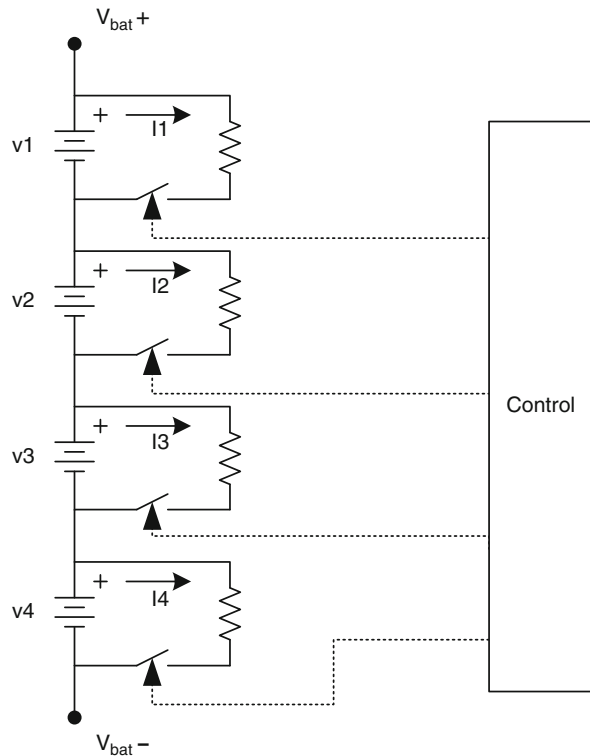
Battery management systems (BMS) for charge equalization monitor the state of charge of each cell. In low-cost applications, a circuit to monitor individual cell voltage may be employed. Switching circuits then control the charge applied to each individual cell in the series during the charging process to equalize the charge on all the cells in the pack.

A good charge/discharge equalization technique should ideally have the following features:

- High efficiency: Implementation of this technique should result in minimum power loss of the system.
- Small volume: Bulky volumes restrict portability and increase cost.
- Simple wiring schemes: Complex wiring schemes increase cost and decrease the reliability.
- In automobile applications, the cell must also be equipped to handle pulse charging from regenerative braking.

Passive Balancing Passive-charge balancing techniques involve bleeding off of charge from the cells with the highest voltage (hence, state of charge) in a battery pack (Fig. 41). A cell with a high charge is indicated by its higher cell voltage. Excess energy is removed through a bypass resistor until the voltage or charge matches the voltage on the weaker cells. Some passive balancing schemes stop charging the battery pack at the instant when any one of the cells in the pack reaches full charge. During discharge operation, they discharge the fully charged cells into a load until these cells reach the same charge level as the weaker cells. These schemes lead to underutilization of the battery pack.

Other schemes are designed to continue charging until all the cells are fully charged but to limit the voltage which can be applied to individual cells and to bypass the cells when this voltage has been reached. The shortcomings of this technique are that this method uses low bypass currents, and hence, equalization times are very long. Also, the battery pack performance is governed by the weakest cell. This process also causes power loss due to the bypass resistors which could drain the battery if operated continuously. It is however very easy to implement and is a low-cost

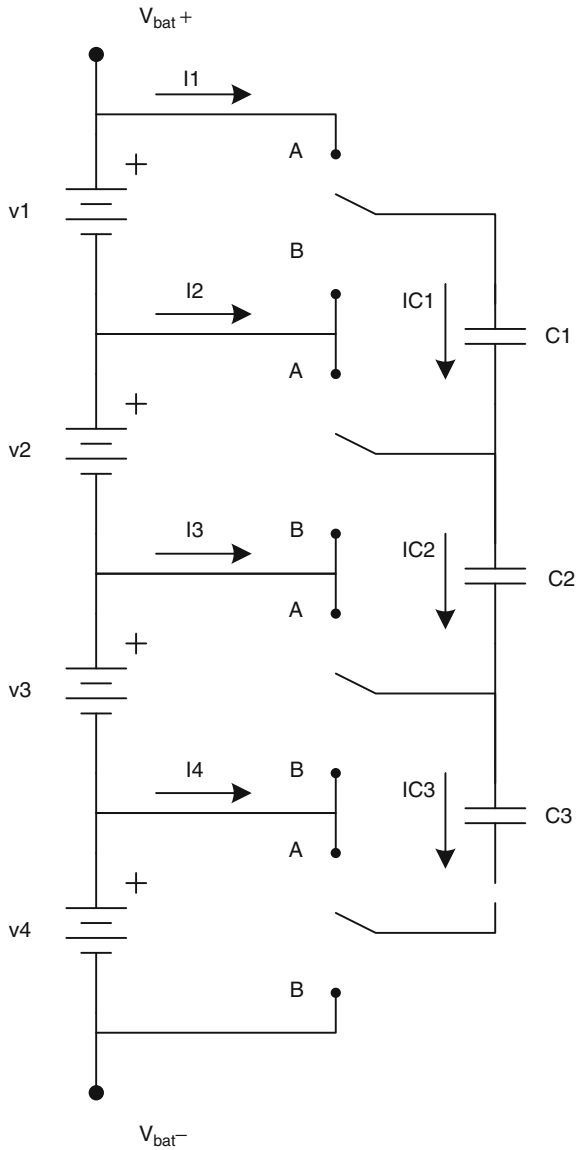


Batteries, Battery Management, and Battery Charging Technology. Figure 41

Passive charge balancing with a dissipative resistor

option. Passive balancing is adequate for both lead-acid and nickel-based batteries, incorporating series string up to about six cells. Passive equalization cannot be employed for charge equalization in Li-ion-based battery strings.

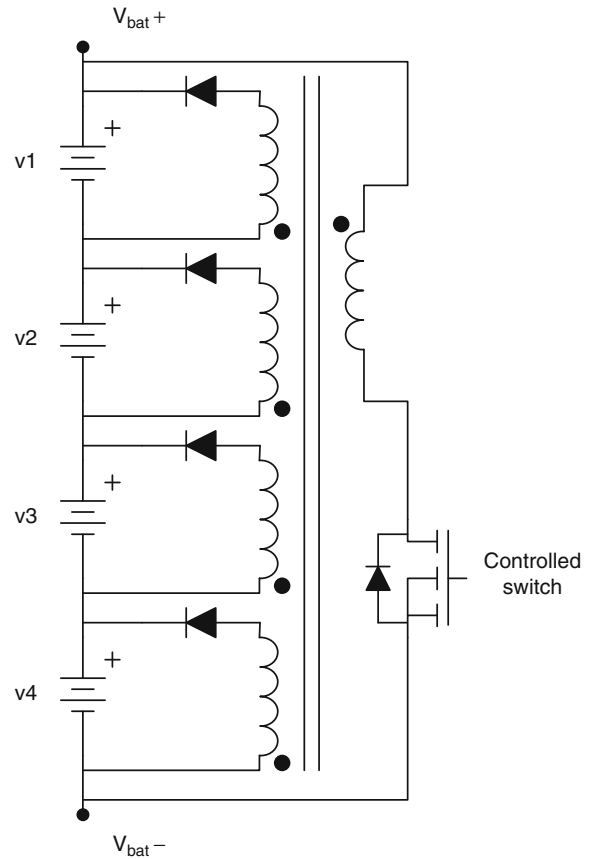
Switched Capacitor The switched capacitor charge equalization method, also called a flying capacitor method, uses a capacitor to transfer charge between cells in a battery pack. Typically, these are adjacent cells in the series string as shown in Fig. 42. When the capacitor is connected to a cell with the higher voltage, the capacitor is charged. When the charged capacitor is connected to a cell with a lower voltage, the capacitor discharges and transfers charge into the new cell. When switched between two cells repeatedly, this movement of charge results in current from the cell with higher voltage to the cell with lower voltage. Finally, cell voltages of all cells in the string reach the same value and voltage equalization is achieved. High-frequency



Batteries, Battery Management, and Battery Charging Technology. Figure 42

Schematic of a switched capacitor equalizer

switching can be accomplished using a single-pole double-throw switch implemented using two sets of MOSFETs. The MOSFETs are switched with frequencies ranging in several kHz. An important feature in the switching scheme is that switches break before make to prevent momentary short circuits of the respective cells. Accordingly, the switch control signals incorporate a dead-band interval. This method is easy to



Batteries, Battery Management, and Battery Charging Technology. Figure 43

A schematic of a flyback-type inductive shuttle charge distribution

implement and it results in reduced losses. A major drawback is that equalization process takes a long time if voltage differences between adjacent cells are small.

Multi-Output Transformer This method uses a transformer with its primary winding connected across the battery and one secondary winding which can be switched across individual cells. Both flyback and forward topologies are employed in practice. Figure 43 illustrates a flyback-based circuit to carry out charge balancing for a battery string. In the flyback structure, when the main switch is switched on, some energy is stored in the transformer magnetic field. When the switch is turned off, the energy is transferred to the secondary of the transformer, similar to the flyback concept. The bulk of the energy is taken up by

cells with lowest cell voltage. The main difference of this method over the switching capacitor scheme is that this method involves taking pulses of energy from the full battery, rather than small charge differences from a single cell, to top up remaining cells. Averaging of the charge level is similar to flying capacitor method, but it avoids the problem of small voltage differences in cell voltage and is consequently much faster. The transformer must have well-balanced secondary windings, otherwise voltage imbalances occur. Also, care must be taken to prevent transformer saturation.

DC-DC Converter Methods This technique involves using power electronics-based converters to transfer energy from higher charged cells to charge-efficient cells in a battery string. Different converter topologies such as the flyback, buck-boost, and Ćuk have been investigated to transfer energy between the batteries. Energy transfer may be unidirectional or bidirectional.

In unidirectional flyback mode, excess energy in the higher charged cell is transferred to the magnetized inductor of the transformer during turn-on operation of the converter. During the turn-off mode, this energy is returned to charge-deficient cells in the battery bank, and thus, charge leveling is achieved. Bidirectional converters are employed to facilitate local energy transfer between two neighboring cells independent of their respective cell voltage. The converters are operated in discontinuous mode to minimize switching losses. The disadvantage is that energy transmission efficiency is low when energy transfer occurs from the first cell to the last with many intermediate stages in a long string. To avoid power loss in intermediate stages, non-isolated buck-boost topologies have been explored in which energy is transferred from the first cell to all other cells in a bank without any intermediary.

Future Direction

Batteries and battery technologies are expected to become even more important in the future as consumers demand longer battery life from consumer electronics; variable energy sources, such as wind and solar, increase in prevalence in the electrical grid; and hybrid and all-electric vehicles become commonplace, to name a few applications currently driving technology development. The emphasis will be to develop

batteries with low cost, high energy density, low weight/volume, completely safe, environmentally friendly, easily disposable, and made from abundant raw materials. Auxiliary battery management systems will become increasingly integrated into the battery pack to create a true “plug and power” energy storage module.

Lithium-based cells hold great promise for the future. Lithium-ion cells have nearly proliferated the consumer electronics market. These batteries are also expected to find a prominent role as ideal electrochemical storage systems in renewable energy plants, as well as power systems for sustainable vehicles, such as hybrid and electric vehicles. However, scaling up the lithium battery technology for these applications is still problematic since issues such as safety, costs, wide operational temperature, and materials availability are yet to be adequately resolved. Safety is an important issue with Li-ion technology, and hence, it forms one of the most important aspects of future research. Lithium-copper cells are seen as the future prospect for lithium-based batteries, although the technology is still in a nascent state. Traditionally, cathodes of Li-based cells have not been reusable and hence the motivation for Li-Cu system which makes provision for reusable electrodes.

Li-air batteries in which oxygen from the air serves as the cathode and lithium as the anode are also being explored and hold promise to increase energy density. Estimates indicated that the lithium-air battery could hold 5–10 times as much energy as a lithium-ion battery of the same weight and double the energy for the same volume. In theory, the energy density could be comparable to that of liquid fuels such as gasoline. However, rechargeable Li-air batteries are still some years away. Flow batteries hold promise for stationary, high-energy applications such as power stations to provide peak loads, backup energy in case of emergencies, and source leveling to mitigate variable production from renewable sources. Zn-Bromine, metal air, vanadium redox are some of the batteries which are being explored for UPS and grid storage applications as an alternative to VRLA batteries, which is currently the standard.

On the battery management side, mobile energy platforms are driving push toward wireless charging technologies and standards for contactless charging.

The Wireless Power Consortium has recently developed the standard for contactless charging called “Qi” for low-powered electronic devices (i.e., less than 5 watts). This standard is suitable for cellular phones and contains interface definition, performance requirements, and compliance testing. Further progress is expected for more powerful chargers for higher-power-consumption devices such as laptops. In the future, all compatible devices with the “Qi” standard will carry the “Qi” logo to show compatibility with “Qi” transmitters. The final goal is to have portable electronic devices charged with the stations with “Qi” logo in airports, railway stations, hotels, etc. Currently, the inductive contactless chargers can transmit power in short distance and with the same speed as wired chargers (e.g., cell phone applications). However, capacitive battery chargers can transmit higher levels of power in shorter time frame. Once the associated costs are alleviated, capacitive contactless charges can dominate the market. It has already started in applications such as a camera flash, where the ability to transfer high power over a short period of time is important. Inductive contactless chargers, however, will remain prime candidates for vehicular-charging applications.

Intermittency of renewable energy systems introduces some integration problems especially for high penetration levels of wind and solar energy systems. The battery energy storage systems are expected to play an important role in addressing intermittency. Appropriate control strategies are under development for charging systems to make wind and solar plant hourly dispatched based on forecasted conditions. Bidirectional converters are a key element here; the battery is charged by the grid during low-demand hours or by wind and solar plants during high-irradiance hours and windy periods. The battery is then discharged to the grid during shading of solar panels or lower wind speeds.

Charging circuitry is also used in stations for electric and plug-in hybrid vehicles (EVs and PHEVs). Three standardized charging levels are defined by the National Electric Code for EVs and PHEVs. Level one method uses 120 V, 15 A (12 A usable) power outlets which are common in residential and commercial units in the USA. However, they prolong the charging period due to limited maximum power (about 1.44 kW). Level two chargers use 240 V, single-phase, 40 A, outlets.

They are known as the “primary” or “preferred” method of charging for PHEVs. There are two types of level two chargers, namely, inductive and conductive (wired). Although level two chargers enable faster charging, they require more safety restriction. Level three chargers use 480 V, 60–150 kW, three-phase power lines. They are intended to charge battery in about 10–15 min, also known as “fast charging” method. One may argue that PHEV batteries can be charged in 1–2 h using level two chargers, and thus, there are less incentives for higher power level three chargers in charging infrastructure for PHEVs.

Integrated battery chargers are an important aspect when considering system-on-chip devices. System-on-chip devices combine different parts of a system, which may conventionally require their own chip, into a single chip. For example, a typical system-on-chip sensor is designed to sense and transmit the data from an inaccessible location to the main controller. It is comprised of an integrated sensor, analog-to-digital converter, micro-controller, memory, and RF transmitter. Usually these system-on-chip sensors must be autonomous systems and thus generate their own power for an extended period of time. The required power for these micro-sensors can be supplied by solar cells or piezoelectric materials. Given the intermittency in the output of solar cell, micro-batteries are required to power the system during the low-light conditions. Therefore, integrated battery charging circuits are one of the essential components of system-on-chip sensors. Integrated battery chargers must meet specific criteria, namely, high efficiency, simple structure, and, most importantly, small size. Size is the prevalent factor in determining the total cost of the system in system-on-chip application. Therefore, in the applications that require extreme integration and low cost, battery is also integrated in the chip together with charger circuit.

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Batteries, Introduction

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Batteries for storage of electricity from solar and wind generation farms are a key element in the success of sustainability. Electric vehicles are the second link in the chain powered by advanced battery systems. This section describes the various devices used in electrochemical energy storage including an overview of electrochemical processes and devices.

► **Nanocarbons for supercapacitors** describes electrochemical capacitors, sometimes called supercapacitors, and are energy storage devices similar to batteries but capable of delivering large amounts of energy in a very short time. These devices rely on the characteristics of the electrical double layer that forms on all conductors when immersed in an electrolyte. The electrical double layer has a high capacitance because the charges are separated on the order of atomic

dimensions. Since there is no mass transfer involved in the delivery of current, response time to a change is 10^{-6} s or faster. As a result, electrochemical capacitors can deliver large amounts of energy in short periods of time. The double layer forms in less than 10^{-6} s and responds to changes in a similar time frame. This is about 1,000 times faster than the electrochemical reaction at a battery electrode that has a time constant in the range of 10^{-3} s. The devices find application wherever power is required to service an application.

► **Electrochemical Supercapacitors and Hybrid Systems** describes electrochemical energy storage devices having higher energy density than electrolytic capacitors and higher power density than batteries. These devices rely on the characteristics of the electrical double layer that forms on all polarized conductors when immersed in an electrolyte. The double layer forms in less than 10^{-6} s and responds to changes in a similar time frame. This is about 1,000 times faster than an electrochemical reaction at a battery electrode that has a time constant in the range of 10^{-3} s. As a result, these can deliver large amounts of energy in a very short time. These devices find application where high power delivery is required.

► **Rechargeable Batteries, Separators for** describes the characteristics of porous membranes that hold the electrolyte and physically separate the negative from the positive electrodes in battery systems. The separator is a key element in battery construction as it physically separates and prevents direct contact (shorting) between the positive and negative electrodes. The separator materials are insulators but have the capability to absorb conducting electrolyte solutions to provide electrical continuity between the anode (negative terminal) and cathode (positive terminal) of the battery system. Each new battery system places new requirements placed on the separator material. The recent growth in the battery industry with the introduction of several new battery systems has resulted in the need to create and optimize new separator materials to meet the market demands. Correspondingly, the demand for novelty in separator membranes, to match the newer battery chemistries and geometries, continues to grow.

► **Lead Acid Battery Systems and Technology for Sustainable Energy** describes the basis for the many different commercial lead acid battery designs and electrical requirements ranging from automotive and

stationary energy storage to sustainable energy storage and power system regulation. The lead acid batteries constitute the single largest battery market segment. The reliability, availability, and low cost are the key to the success of the lead acid system. It is among the greenest of battery systems because of its established recycling industry. The ability to adapt the system to new applications and to optimize their performance to meet the demands of new applications has been a successful international effort for 150 years and continues to generate improved battery designs and power systems for the future.

While graphite is the material of choice for the anode in present commercial lithium ion batteries, an active search to identify a new high-energy anode material has identified ► [silicon-based anodes for Li-ion batteries](#) as a promising replacement for the graphite anode material. The silicon-lithium alloy has promise to significantly increase the cell capacity up to ten times that of the present graphite lithium anode. The successful transition will require developing method to handle the volume change characteristic of the silicon materials without disintegration of the anode structure. Strategies are based on fundamental mechanistic research to better understand the electrochemical lithiation and delithiation processes of silicon materials during charge-discharge cycling in terms of crystal structure, phase transitions, morphological changes, and reaction kinetics. It is expected that a viable silicon nanostructure anode can be developed with three to five times the capacity of graphite.

► [Nickel-based battery systems](#) describes the progression of higher-energy nickel cathode battery systems starting with iron for electric vehicle applications; followed by cadmium, metal hydride, hydrogen, and zinc anodes and their high power and good cycle life; and ending with nickel-hydrogen batteries for long life in space applications. At the turn of the twentieth century, simultaneously, Edison in the USA and Junger in Sweden independently developed the nickel-iron rechargeable battery system. The system powered the first electric vehicles in the early 1900s and is still produced today for long-life energy storage applications.

► [Lithium Ion Batteries, Electrochemical Reactions in](#) details the various advanced experimental techniques that are used to define the characteristics of new high performance materials as well as improve

the performance of existing materials for lithium ion batteries. X-ray, neutron and nuclear magnetic resonance techniques, etc. each provide essential complementary information on solid materials on the crystal structure of new and potential cathode and anode materials at an atom level leading to improved performance of existing materials as well as identifying potential high performance new materials.

► [Medical Device Batteries](#) describes wearable and implantable medical devices powered by batteries. Devices include those that are used for cardiac rhythm management (pacemakers, defibrillators, and heart failure devices), hearing loss, bone growth and fusion, drug delivery for therapy or pain relief, nerve stimulation for pain management, urinary incompetence and nervous system disorders, vision, diagnostic measurements and monitoring, and mechanical heart pumps.

► [Lithium-Ion Battery Systems and Technology](#) batteries have revolutionized battery powered electronic devices with its light weight, high energy storage capability, and long cycle life. Since its introduction in 1991, it has grown to a \$4+ billion market in 2010 and dominated powering the modern portable electronic devices. It replaced nickel cadmium and nickel metal hydride batteries and is positioned to power the electric vehicle market in the near future. The prime reasons for its rapid success and proliferation in consumer electronic market are high unit cell voltage, high energy density, and long cycle and shelf life with no memory effect. The significant progress of Li-ion batteries is mainly due to numerous innovations and advancements in materials, designs, and safety. This entry is intended to provide an overview of Li-ion batteries on several aspects. Starting with a brief discussion on its history, commercial success, and working mechanism, all the critical components inside the cell have been discussed with adequate details. The later part of this entry will primarily focus on manufacturing process with detailed discussion on cell-level safety, followed by overview of recent advances and modern trends in Li-ion systems.

► [Lithium-ion Batteries, safety](#) provides an overview of the safety considerations for Li-ion cells. Presently, Li-ion cells have a record of field failures or safety incident of one incident every ten million cells. The 18650 cell used in portable electronic applications contains sufficient energy to self-heat the cell to over

600°C. This does not include oxidation of the electrolyte solvent by the cathode oxide materials. Adiabatically, including the electrolyte, the temperature is significantly higher. The causes of an incident include overcharge and heating from external sources. All cells have safety devices such as PTC, CID, vents, and safety circuitry. An internal short is the most common trigger for a safety incident.

► **Lithium Battery Electrolyte Stability and Performance from Molecular Modeling and Simulations** provide an example of the power of this experimental technique. Molecular orbital calculations have proven useful and have the capability to identify the details of lithium insertion into battery-related materials and to identify new cathode materials as well as improve the performance of existing materials. Crystallite size has tremendous effect to the thermodynamics and kinetics in intercalation compounds and impacts the diffusion/transport length, effective reaction surface area, surface energy, and interphase energy. Also, the experimental verification of one-dimensional lithium diffusion in Li_xFePO_4 was confirmed.

► **Battery cathodes** provides an overview of the current cathode materials available for use in Li-ion batteries and a discussion of the various battery systems. Li-ion batteries are dual intercalation systems, in which both the cathode and the anode have structures that allow reversible insertion and extraction of lithium cations. In principle, there are numerous materials that undergo reversible intercalation and can serve as electrode materials. Hence, unlike the lead acid battery which describes a specific chemistry, the chemistry of the Li-ion battery is not fixed but determined by the choice of anode and cathode materials.

► **Olivine Phosphate Cathode Materials, Reactivity and Reaction Mechanisms** provide a summary of the characteristics of the phosphate cathode materials. The interest in phosphates was triggered by the work of Goodenough in identifying lithium iron phosphate, LiFePO_4 , as a promising cathode material for use in Li-ion battery systems. The nanosize crystal structure gives the material unique properties including high surface area, very long cycle life, and, just as important, a low-cost cathode material.

The ► **Battery Components, Active Materials** for reviews the role played by the pioneers Volta, Daniell, Davy, Galvani, Faraday, and Davie in providing the

basis for batteries as they are known today. The key to identifying new battery materials is found in the fundamental properties of the materials and is the route to improve performance of present materials as well as the identification of new materials with long-life capability.

Battery Cathodes

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Article Outline

Glossary
Definition of the Subject and Its Importance
Introduction
Characteristics of Battery Cathode Materials
Future Directions
Acknowledgments
Bibliography

Glossary

Anode – (negative electrode) This electrode donates electrons during cell discharge.

Battery A device consisting of one or many electrochemical cells connected together, in which chemical energy is converted into power. These can be further categorized as primary (non-rechargeable) or secondary (rechargeable) systems.

Capacity The amount of charge that a battery contains, often expressed as mAh or Ah. This depends on the size of the battery and its chemistry. Rated capacity also depends on the current used.

Cathode – (positive electrode) This electrode accepts electrons during cell discharge.

Cell One unit of a battery, commonly consisting of an anode, a cathode, an electrolyte, a separator, and two current collectors.

Energy density or specific energy Energy per unit volume or weight of a material or a device, respectively, often expressed as Wh/L or Wh/kg. Energy is

a product of the cell voltage and capacity per unit volume or weight.

Intercalation compound (host material, insertion compound) Originally, this referred specifically to layered structures that can undergo insertion of ions or molecules between the van der Waals gaps, but is now commonly used for any structure that undergoes topotactic insertion reactions. For Li-ion battery materials, it refers specifically to compounds that undergo reductive insertion of lithium ions, such as graphite (used as an anode) or LiCoO_2 (used as a cathode).

Jahn–Teller effect The geometric distortion of nonlinear complexes of certain transition metal ions to remove degeneracy. For example, Mn(III) in octahedral coordination is expected to have an electronic configuration of $t_{2g}^3 e_g^1$. Elongation along one axis of the octahedron, for example, decreases the symmetry and removes the degeneracy.

Power density and specific power Power per unit volume or weight, respectively, often expressed as W/L or W/kg. Power is the product of the current and the operating voltage. This is a function both of the materials used and the cell design.

Practical energy density or specific energy Based on the entire weight or volume of the device including inert components. It may be only 1/4–1/2 of the theoretical energy density. It may also refer only to the useable portion of the theoretical capacity of the anode or cathode material itself.

Ragone plot A plot showing the relationship between energy density and power density for any particular battery chemistry. This relationship is a function both of battery design and chemistry for Li-ion batteries.

Solid electrolyte interface (SEI) A very thin (nanometer scale) layer formed on a lithium or lithiated graphite anode, which develops upon reaction with certain kinds of electrolytic solutions. The SEI is a specific kind of reaction layer that is ionically conductive but electronically insulating. It passivates the electrode, preventing further reaction with the electrolytic solution, and allows reversible operation of the device.

Specific capacity The amount of charge per unit weight that a battery electrode material contains, often expressed as mAh/g. This is a fundamental

characteristic of the material, and depends upon its redox chemistry and structure.

Theoretical energy density, specific energy, capacity Based on weight or volume of the electrode active materials only.

Topotactic transformation A transformation in a crystal lattice involving displacement or exchange of atoms, which maintains the basic structure.

Definition of the Subject and Its Importance

In a discharging battery, the cathode is the positive electrode, at which electrochemical reduction takes place. As current flows, electrons from the circuit and cations from the electrolytic solution in the device move toward the cathode. Although these processes are reversed during cell charge in secondary batteries, the positive electrode in these systems is still commonly, if somewhat inaccurately, referred to as the cathode, and the negative as the anode. Because this terminology is widespread throughout the Li-ion battery literature, this usage will be adopted for this article.

Li-ion batteries are dual intercalation systems, in which both the cathode and the anode have structures that allow reversible insertion and extraction of lithium cations. In principle, there are numerous materials that undergo reversible intercalation and can serve as electrode materials. Hence the chemistry of the Li-ion battery is not fixed, unlike the great majority of battery systems. The choice of cathode greatly affects the performance and cost of a Li-ion battery; for example, it is a major determinant of energy density, since it typically has a lower specific capacity than the most common anode material, graphite (372 mAh/g), to which it must be matched.

Introduction

The very high theoretical capacity of lithium (3,829 mAh/g) provided a compelling rationale from the 1970s onward for the development of rechargeable batteries employing the elemental metal as an anode. The realization that some transition metal compounds undergo reductive lithium intercalation reactions reversibly allowed the use of these materials as cathodes in these devices, most notably, TiS_2 [1–3]. Another intercalation compound, LiCoO_2 , was described shortly thereafter [4, 5] but, because it was produced

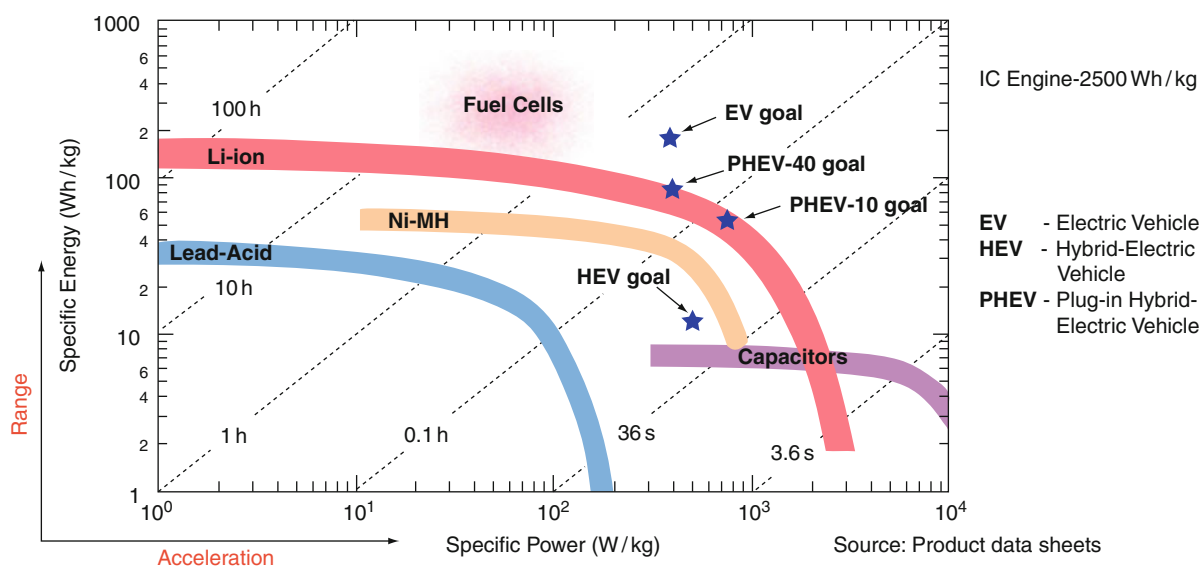
in the discharged state, was not considered to be of interest by battery companies at the time.

Due to difficulties with the rechargeability of lithium and related safety concerns, however, alternative anodes were sought. The graphite intercalation compound (GIC) LiC_6 was considered an attractive candidate [6] but the high reactivity with commonly used electrolytic solutions containing organic solvents was recognized as a significant impediment to its use. The development of electrolytes that allowed the formation of a solid electrolyte interface (SEI) on surfaces of the carbon particles was a breakthrough that enabled commercialization of Li-ion batteries [7]. In 1990, Sony announced the first commercial batteries based on a dual Li-ion intercalation system [8]. These devices are assembled in the discharged state, so that it is convenient to employ a prelithiated cathode such as LiCoO_2 with the commonly used graphite anode. After charging, the batteries are ready to power devices.

The practical realization of high energy density Li-ion batteries revolutionized the portable electronics industry, as evidenced by the widespread market penetration of mobile phones, laptop computers, digital music players, and other lightweight devices, since the early 1990s. In 2009, worldwide sales of Li-ion batteries

for these applications alone were US\$7 billion [9]. Furthermore, their performance characteristics (Fig. 1) make them attractive for traction applications such as hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and electric vehicles (EVs); a market predicted to be potentially ten times greater than that of consumer electronics. In fact, only Li-ion batteries can meet the requirements for PHEVs as set by the US Advanced Battery Consortium (USABC), although they still fall slightly short of EV goals.

In the case of Li-ion batteries, the trade-off between power and energy shown in Fig. 1 is a function both of device design and the electrode materials that are used. Thus, a high-power battery (e.g., one intended for an HEV) will not necessarily contain the same electrode materials as one designed for high energy (i.e., for an EV). As is shown in Fig. 1, power translates into acceleration, and energy into range, or miles traveled, for vehicular uses. Furthermore, performance, cost, and abuse-tolerance requirements for traction batteries [11] differ considerably from those for consumer electronics batteries. Vehicular applications are particularly sensitive to cost; currently, Li-ion batteries are priced at about US \$1,000/kWh, whereas the USABC goal is US \$150/kWh [12]. The three most



Battery Cathodes. Figure 1

A Ragone plot, showing the relationship between specific power and specific energy for several types of electrochemical devices. Goals set by FreedomCar for HEV, PHEVs, and EVs are also indicated (Used with permission from [10])

expensive components of a Li-ion battery, no matter what the configuration, are the cathode, the separator, and the electrolyte [13]. Reduction of cost has been one of the primary driving forces for the investigation of new cathode materials to replace expensive LiCoO_2 , particularly for vehicular applications. Another extremely important factor is safety under abuse conditions such as overcharge. This is particularly relevant for the large battery packs intended for vehicular uses, which are designed with multiple cells wired in series arrays. Premature failure of one cell in a string may cause others to go into overcharge during the passage of current. These considerations have led to the development of several different types of cathode materials, as will be covered in the next section. Because there is not yet one ideal material that can meet requirements for all applications, research into cathodes for Li-ion batteries is, as of this writing, a very active field.

Characteristics of Battery Cathode Materials

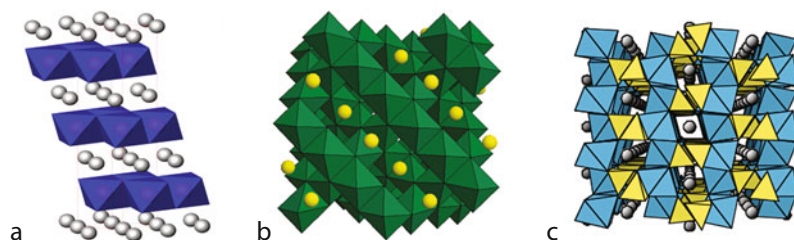
Modern cathode materials for Li-ion batteries are generally prepared in the lithiated (discharged) state, so that they can be paired with delithiated anodes such as graphite. For ease of handling, it is desirable that the material be reasonably air-stable at room temperature. Furthermore, graphite anodes impose a penalty of approximately 0.1 V in average cell potential compared to Li metal. To compensate for this, and also to maximize energy density, cathodes intended for use in

Li-ion batteries have higher average potentials versus Li/Li^+ than earlier materials such as TiS_2 and vanadates [14] developed for Li metal batteries. Furthermore, the requirement for high specific capacity generally restricts choices to compounds containing first-row transition metals (usually Mn, Fe, Co, and Ni). Environmental and toxicity concerns have precluded the development of most V or Cr-containing materials, although electroactive compounds containing these metals exist. Today's technologically important cathodes fall into two broad categories: metal oxides and polyanionic compounds.

Figure 2 shows representations of the crystal structures of the most commonly used cathode materials for Li-ion batteries, and Table 1 summarizes their general properties. Figure 3 shows typical discharge profiles of selected materials in Li half-cell configurations.

Layered Transition Metal Oxides

LiCoO_2 was the first of the layered transition metal oxides to be commercialized, and is still used today in batteries for consumer devices. It has the structure shown in Fig. 2a, where Co and Li, located in octahedral sites, occupy alternating layers along the 111 planes in a cubic close-packed (ccp) oxygen array, to form a structure with overall hexagonal symmetry (space group $R\bar{3}m$). This type of stacking arrangement is called O3 in layer notation, indicating that there are three transition metal layers per unit cell and the Li ions are octahedrally coordinated.

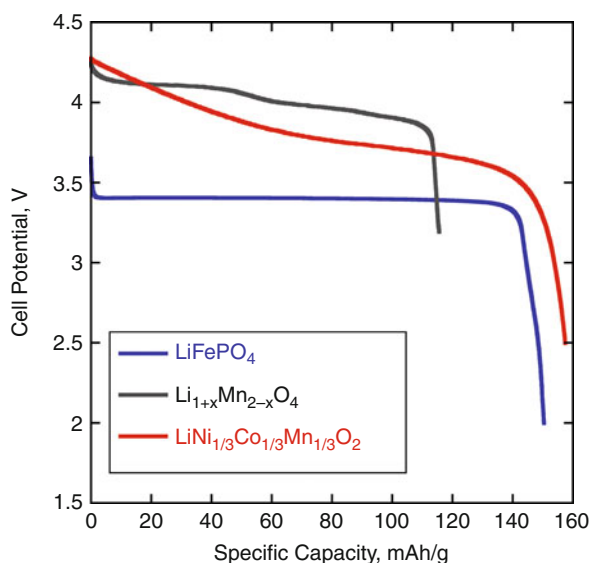


Battery Cathodes. Figure 2

Structures of common cathode materials: (a) The layered structure of LiCoO_2 with c -axis oriented vertically. The octahedrally coordinated Li ions in $3a$ sites are represented as spheres and CoO_6 (Co in $3b$ sites) as octahedra; (b) the cubic structure of LiMn_2O_4 spinel, with tetrahedrally coordinated Li ions (in $8a$ sites) represented as spheres, and MnO_6 (Mn in $16d$ sites) as octahedra; and (c) the olivine structure of LiFePO_4 , looking down the b -axis. Octahedrally coordinated Li ions are represented as spheres, and FeO_6 and PO_4 as octahedra and tetrahedra, respectively

Battery Cathodes. Table 1 Characteristics of commercial Li-ion battery cathode materials

Material	Structure	Potential versus Li/Li ⁺ , average V	Specific capacity, mAh/g	Specific energy, Wh/kg
LiCoO ₂	Layered	3.9	140	546
LiNi _{0.8} Co _{0.15} Al _{0.05} O ₂ (NCA)	Layered	3.8	180–200	680–760
LiNi _{1/3} Co _{1/3} Mn _{1/3} O ₂ (NMC)	Layered	3.8	160–170	610–650
LiMn ₂ O ₄ and variants (LMO)	Spinel	4.1	100–120	410–492
LiFePO ₄ (LFP)	Olivine	3.45	150–170	518–587

**Battery Cathodes. Figure 3**

Discharge profiles of lithium cells containing LiFePO₄, Li_{1+x}Mn_{2-x}O₄, or LiNi_{1/3}Co_{1/3}Mn_{1/3}O₂ electrodes

Delithiation proceeds topotactically [15, 16] and is reversible over the composition range $1 \geq x \geq \sim 0.5$ for x in Li_xCoO₂, giving a practical specific capacity of about 140 mAh/g below 4.2 V versus Li/Li⁺. Extraction of lithium to values of $x < \sim 0.5$ results in higher practical capacities initially, but often increases cycling losses [17]. This has been attributed to side reactions involving particle surfaces, which increase cell impedance, and to structural instability associated with phase changes at very low values of x in Li_xCoO₂ [18–21]. Coating LiCoO₂ particles, or rigorous heat treatment to remove surface species [22–24], results in improved cycling below 4.5 V versus Li/Li⁺, but full delithiation is still not possible without cycling losses.

A layered compound with the nominal composition of LiNiO₂ has also been extensively studied for battery applications [25–28]. Its lower cost compared to LiCoO₂, and the potential for higher energy density were driving forces for its development. Although the structure is similar to LiCoO₂, LiNiO₂ readily exhibits non-stoichiometry. During synthesis, there is a tendency toward loss of lithium and reduction of some Ni to the +2 oxidation state. The Ni²⁺ migrates to Li⁺ 3a sites, due to the similarities in size between the two types of ions. The actual composition can be written as Li_{1-z}Ni_{1+z}O₂ with $0 < z < 0.2$, or as (Li_{1-z}Ni_z²⁺)_{3a}(Ni_z²⁺Ni_{1-z}³⁺)_{3b}O₂ [29]. The degree of disorder is influenced by the synthetic conditions, and the electrochemical properties (e.g., the first cycle reversibility) are affected by the degree of non-stoichiometry [30, 31]. The difficulty in synthesizing high-quality LiNiO₂ was one impediment to its widespread adoption as a cathode material in Li-ion batteries, although nearly ideal structures can be obtained if sufficient care is taken [29]. (However, perfectly stoichiometric LiNiO₂ materials probably do not exist). Partial substitution of Ni with Co [32] was later found to be effective at reducing the cationic disorder on 3a sites, leading to compositions such as LiNi_{0.8}Co_{0.2}O₂. Cobalt also helps to reduce oxygen loss at high states-of-charge, improving safety.

The thermal instability of Li_xNiO₂ at high states-of-charge [33–36] also raised a great deal of concern about the safety of this material when used as a cathode. The properties of LiNiO₂ have been improved via coating and doping with Mg, leading to a very high-capacity electrode material [37] with better thermal properties. However, the most commonly

used electrode material related to LiNiO_2 is $\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$ or NCA, which is now commercially produced (see Table 1 for general properties). The presence of Al in NCA improves both the thermal [33–36] and electrochemical properties [38, 39]. The high specific capacity and good power capability of this material make it attractive for vehicular applications although it is still not considered as inherently safe as other candidates such as LFP (see Table 2 and the discussion of olivines below).

Battery Cathodes. Table 2 Relative merits of selected commercial Li-ion battery cathodes

Advantages	Disadvantages
LMO (LiMn_2O_4 and variants)	
Low cost Excellent high rate performance High operating voltage No resource limitations Moderate safety (oxygen release)	Mn solubility issue, affecting cycle life Low capacity
LFP (LiFePO_4 and variants)	
Moderately low cost Excellent high rate performance No resource limitations Very slow reaction with electrolyte Excellent safety (no oxygen release)	Low operating voltage Low capacity, especially for substituted variants Controlling patents
NMC ($\text{LiNi}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}\text{O}_2$) and variants	
High capacity High operating voltage Slow reaction with electrolytes Moderate safety (oxygen release)	High cost of Ni and Co Potential resource limitations Relatively new in performance Controlling patents
NCA ($\text{LiNi}_{0.8}\text{Co}_{0.15}\text{Al}_{0.05}\text{O}_2$)	
Performance is well established Slow reaction with electrolytes High capacity High voltage Excellent high rate performance	High cost of Ni and Co Potential resource limitations Controlling soft patents

Several ternary Li-Fe-O phases exist with differing arrangements of cations in cubic close-packed oxygen arrays [40]. However, LiFeO_2 with the R-3m structure is metastable and generally must be prepared via indirect methods such as ion exchange of NaFeO_2 . The electrochemical properties of this material [41] and most other polymorphs [42, 43] are not, however, suitable for lithium-ion batteries due to low and highly sloping voltage profiles or poor cycling properties. Li_5FeO_4 with the anti-fluorite structure has a potential profile that may be compatible in a Li-ion battery configuration, but delithiation does not appear to proceed via simple oxidative deintercalation [44]. This material has been proposed for use as a lithium-ion source for lithium-ion batteries (i.e., to lithiate graphite anodes so that cathodes in the charged state may be used).

Ternary Li-Mn-O phases with Mn in the +3 or +4 oxidation state crystallize as spinels, the rock salt structure Li_2MnO_3 , or as orthorhombic LiMnO_2 with a corrugated structure (o- LiMnO_2) but not as O3 layered structures. Lithium manganese oxide spinels (LMO) are technologically important cathodes and will be considered in a later section (*vide infra*). The Na-Mn-O system contains numerous polymorphs, including layered structures. NaMnO_2 has the same stacking arrangement as LiCoO_2 , but is monoclinically distorted (space group C2/m), due to the abundance of Jahn–Teller distorted Mn^{3+} ions. Ion exchange of this compound yields a layered LiMnO_2 (designated O'3, with the prime indicating the monoclinic distortion) [45], but it rapidly converts to spinel upon electrochemical cycling, as does orthorhombic LiMnO_2 [46]. O'3- LiMnO_2 , o- LiMnO_2 , and spinel manganese oxide all have cubic close-packed oxygen arrays and differ only in the cation arrangement. Upon electrochemical delithiation of the first two materials, disproportion of Mn^{3+} into Mn^{2+} and Mn^{4+} ions occurs and Mn^{2+} ions subsequently migrate into vacant sites in the lithium layers via low-energy pathways, facilitating structural rearrangement to spinel [47].

Lithium-deficient layered $\text{Li}_x\text{MnO}_{2+y}$ ($x \approx 0.7$, $y \geq 0.05$), which has an O2 rather than O3 stacking arrangement, does not convert to spinel upon cycling [48, 49], because the oxygen array is not ccp. In addition, non-stoichiometric lithium manganese oxides that are intergrowths of O2 and O3 phases show better

resistance to conversion than the pure O3 structure [50, 51]. The presence of transition metal vacancies in these compounds (which reduce the concentration of the Jahn–Teller Mn^{3+} ions) results in low rate capability, because the vacancies tend to trap nearby lithium ions, impeding their mobility [52].

Other lithium manganese oxides with tunnel structures [53–55] exhibit interesting electrochemical properties, particularly those based on the $\text{Na}_{0.44}\text{MnO}_2$ structure. This material has excellent cycling characteristics [56] and rate capability [57], and does not convert to spinel, although the practical capacity is limited by voltage considerations (the average potential at which lithium is extracted is the highest of any known manganese oxide [58]). All of these tunnel and O2 or O2/O3 layered materials, however, must be prepared via ion exchange of their sodium manganese oxide structural analogs, complicating their preparation. Furthermore, the lithium deficiency of the ion-exchanged materials limits the capacity in Li-ion battery configurations, as all of the cycleable lithium must originate from the cathode.

Li_2MnO_3 can be considered a layered structure similar to LiCoO_2 , but with 111 planes alternately occupied by Li and $\text{Li}_{1/3}\text{Mn}_{2/3}$. Ordering of Li and Mn in the transition metal layer imposes a monoclinic superstructure, but the stacking arrangement is essentially identical to that of the R-3m structures discussed above. Mn in this compound is tetravalent and all lithium sites are occupied, precluding either oxidative deintercalation or reductive intercalation. Nevertheless, several researchers have observed electrochemical activity of Li_2MnO_3 when it is charged in lithium half-cells to high potentials [59]. Recent evidence [60] suggests that lithium deintercalation occurs with simultaneous oxygen loss during the initial charge, as well as H^+/Li^+ exchange. The converted material becomes electroactive and can subsequently be lithiated during cell discharge. Acid leaching of Li_2MnO_3 also yields an electroactive manganese oxide phase [61]. The reaction involves loss of Li_2O from the structure and ion exchange, to produce layered $\text{H}_{1-x}\text{Li}_x[\text{Li}_{0.33}\text{Mn}_{0.67}]\text{O}_2$ [62].

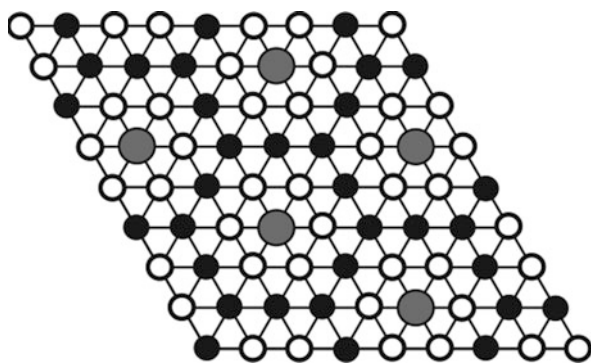
The compound $\text{Li}_{1.2}\text{Mn}_{0.4}\text{Cr}_{0.4}\text{O}_2$ [63] is essentially a solid solution of layered Li_2MnO_3 and LiCrO_2 with an O3 stacking arrangement [64]. Very high discharge capacities (~ 200 mAh/g) can be obtained based on

$\text{Cr}^{3+} \leftrightarrow \text{Cr}^{6+}$ redox processes. Conversion to spinel phases does not occur because Mn remains in the +4 oxidation state throughout charge and discharge, nor does the electrode need chemical or electrochemical activation prior to use. Nevertheless, concerns over the environmental impact of hexavalent chromium have prevented further development of this material.

The search for improved layered oxide materials containing low-cost transition metals ultimately led to the discovery of $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ [65–67] as well as compounds with the general composition $\text{Li}[\text{Ni}_x\text{Li}_{(1/3-2x/3)}\text{Mn}_{(2/3-x/3)}]\text{O}_2$ [68]. Computational modeling [69] and spectroscopic investigations [70] show that the Ni and Mn in these materials are in the +2 and +4 oxidation states, respectively. During normal charge processes in an electrochemical cell, nickel is ultimately oxidized to the +4 oxidation state, and Mn remains tetravalent. $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ does not convert to spinel upon cycling, unlike the metastable O3- LiMnO_2 , because no trivalent Mn is ever produced in the structure.

The defect chemistry of $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ also distinguishes it from LiNiO_2 (where nickel is primarily in the +3 oxidation state initially) discussed above. A feature of $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ is anti-site mixing [65–67, 71, 72] in which some Ni^{2+} ions are located on the Li 3a sites, and some Li^+ ions on transition metal 3b sites, that is, $(\text{Li}_{1-x}\text{Ni}_x)_{3a}(\text{Li}_x\text{Ni}_{0.5-x}\text{Mn}_{0.5})_{3b}\text{O}_2$, $x \approx 0.08–0.12$. Mn ions in the transition metal layers preferentially surround the Li ions located in 3a sites to form Li_2MnO_3 -like clusters, and Ni ions occupy sites adjacent to Mn, to form a “flower pattern” (Fig. 4). The anti-site mixing is thought to be a thermodynamically favored feature of the ion ordering and thus intrinsic to the structure. Unlike with LiNiO_2 , simple manipulation of conditions during direct synthesis is therefore not likely to result in a near-ideal layered structure.

$\text{Li}[\text{Ni}_x\text{Li}_{(1/3-2x/3)}\text{Mn}_{(2/3-x/3)}]\text{O}_2$ compounds can be considered solid solutions of Li_2MnO_3 and $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$. Although the discharge capacity between 4.4 and 3.0 V versus Li/Li⁺ drops as the Ni content decreases, the opposite trend is observed after cell charge to 4.8 V and subsequent discharge to 2.0 V [73]. In addition, the Li_2MnO_3 -rich materials exhibit a plateau at about 4.5 V during charge, the length of which is inversely proportional to x . This is thought to be deintercalation of Li ions with concomitant loss of



Battery Cathodes. Figure 4

A transition metal layer in $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ showing the flower pattern. Li is represented by the large gray circles, Mn by small white circles, and Ni by black circles (Used with permission from Ref. [71])

oxygen (for a net loss of Li_2O), similar to what happens when Li_2MnO_3 is charged in an electrochemical cell. This process can result in very high discharge capacities upon subsequent cycles (e.g., 230 mAh/g for $x = 1/3$). An advantage to these materials and related Li-rich materials (where excess lithium replaces some of the transition metal ions on $3b$ sites, but the Mn content still equals that of the Ni content) is decreased cation mixing. This improves rate capability [74] as compared to $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$.

The presence of a relatively large number of Ni ions in the Li $3a$ sites of the $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ structure due to the anti-site mixing has a negative impact on the Li diffusivity, resulting in a low-rate cathode material. $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$, prepared by low-temperature ion exchange of the nearly perfectly layered $\text{NaNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ analog, is capable of sustaining higher discharge currents than samples prepared by conventional methods [75]. However, the most successful method used to address this issue has been to incorporate some cobalt into the structure [76]. The best known of these compounds is $\text{Li}[\text{Ni}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}]\text{O}_2$, sometimes referred to as NMC (Tables 1 and 2). This compound is gradually replacing LiCoO_2 in consumer batteries (in some cases, a mixture of the two are used as the cathode) and is under consideration for some vehicular applications. The voltage profile of NMC versus Li/Li^+ is gradually sloping (Fig. 3), as is typical of many layered compounds, and provides a somewhat

higher capacity than LiCoO_2 below 4.3 V versus Li/Li^+ (typically about 160 mAh/g compared to 140). Capacities in excess of 200 mAh/g can be achieved when cells are charged to higher voltage limits, although this usually results in diminished cycle life.

The oxidation states of Ni, Co, and Mn in as-made $\text{Li}[\text{Ni}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}]\text{O}_2$ are +2, +3, and +4, respectively [77]. First principle calculations suggest that Ni^{2+} is ultimately oxidized to Ni^{4+} during extraction of the first two-thirds of the lithium during electrochemical charging in lithium cells, and oxidation of Co^{3+} to Co^{4+} occurs only during removal of the last one-third [78] (i.e., at high cell potentials). As in $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$, Mn remains inactive throughout normal operating cell voltages. The redox activity of Ni during the extraction of lithium from $\text{Li}[\text{Ni}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}]\text{O}_2$ has been verified by in situ X-ray absorption spectroscopic (XAS) studies, although the details of the participation of Co in the electrochemistry are less clear [79–83]. Charge compensation associated with Co is currently thought to occur, at least partially, at oxygen sites, due to the covalency of the Co–O bonds.

The improved electrochemical properties and better structural, chemical, and thermal stability [84, 85] of $\text{Li}[\text{Ni}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}]\text{O}_2$ compared to LiCoO_2 or NCA render it an attractive replacement cathode material for consumer batteries. Nevertheless, the presence of a significant amount of costly cobalt, albeit in reduced quantities compared to LiCoO_2 , may still make it too expensive for most vehicular applications. Compounds having the general formula $\text{Li}[\text{Ni}_x\text{Co}_{1-2x}\text{Mn}_x]\text{O}_2$ with $x = 0.4$ or 0.45 have recently been developed by Whittingham and coworkers specifically to address the cost issue [86–89]. Although the amount of anti-site mixing increases with larger x , these materials exhibit very good electrochemical performances. The effect of increasing the Ni content of these materials on the thermal stability, especially at high states of charge, remains to be determined, however.

Another approach has been to partially substitute another metal such as aluminum for cobalt [89, 90]. Although the amount of substitution must be kept low to maintain the high specific capacities, both the thermal stability of the delithiated materials [91] and the electrochemical properties [92, 93] appear to be enhanced.

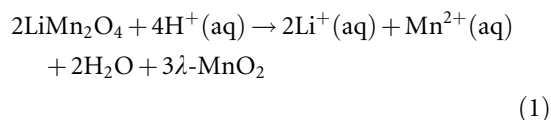
All of the NMCs discussed above contain equal amounts of Ni and Mn, which ensure that the oxidation states of the two metals are primarily +2 and +4, respectively. Recent attempts to increase Mn content in stoichiometric materials having the formula $\text{Li}[\text{Ni}_{0.45-x}\text{Co}_{0.1}\text{Mn}_{0.45+x}]\text{O}_2$ yielded phase mixtures for values of $x > 0.05$ [94] and a solid solution phase for $x = 0.05$. In this compound, $\text{Li}[\text{Ni}_{0.4}\text{Co}_{0.1}\text{Mn}_{0.5}]\text{O}_2$, the extra manganese is in the +3 oxidation state. Unfortunately, this material exhibits poorer capacity retention upon electrochemical cycling and lower rate capability than $\text{Li}[\text{Ni}_{0.45}\text{Co}_{0.1}\text{Mn}_{0.45}]\text{O}_2$. It is, however, possible to form solid solutions between $\text{Li}[\text{Ni}_{1/3}\text{Co}_{1/3}\text{Mn}_{1/3}]\text{O}_2$ and Li_2MnO_3 to make Li- and Mn-rich materials where the excess Mn is in the +4 oxidation state. As with the related $\text{Li}[\text{Ni}_x\text{Li}_{(1/3-2x/3)}\text{Mn}_{(2/3-x/3)}]\text{O}_2$ compounds, these materials can be electrochemically activated during charge to high potentials in lithium cells. The activation process (deintercalation of Li, concomitant loss of oxygen, and H^+/Li^+ ion exchange) yields electrodes with discharge capacities as high as 290 mAh/g [95, 96]. The very high capacities make these materials interesting for both consumer and automotive applications, and they are now being actively developed (e.g., by Envia Systems, Newark, CA).

Manganese Oxide Spinel

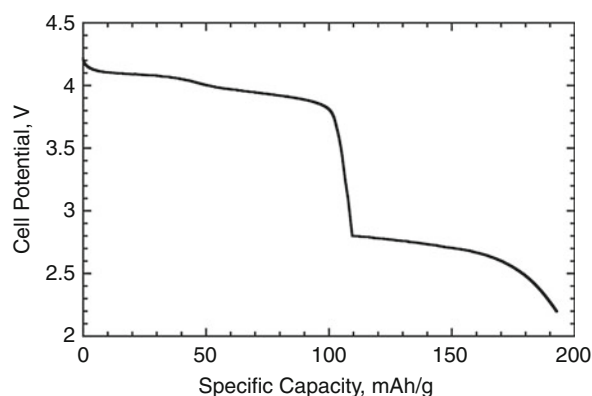
The marked tendency for many manganese oxide phases to convert to spinel structures during lithiation in electrochemical cells, or upon heating with a lithium source, attests to the stability of this structure in the Li-Mn-O system. The stoichiometric spinel, LiMn_2O_4 , is easily synthesized in air from a variety of Li and Mn-containing precursors. Figure 2b shows its cubic structure (space group $\text{Fd-}3\text{m}$), where Li ions occupy tetrahedral $8a$ sites and Mn is located in octahedral $16d$ sites in a ccp array of oxygen anions. In addition, there are vacant tetrahedral and octahedral interstitial sites in the three-dimensional structure that provide pathways for lithium diffusion.

Early work [97] showed that it is possible to remove lithium from LiMn_2O_4 using a mild acid treatment. During this process, Mn is oxidized from an average +3.5 oxidation state to +4, and $\lambda\text{-MnO}_2$, which retains

the spinel framework, is formed (Eq. 1). In addition, some dissolution of Mn occurs:



Oxidative extraction of lithium from the tetrahedral $8a$ sites of LiMn_2O_4 to form $\lambda\text{-MnO}_2$ in a lithium cell [98, 99] was subsequently demonstrated to occur slightly above 4 V. It is also possible to insert lithium into the vacant octahedral sites of LiMn_2O_4 either chemically or electrochemically, with concomitant reduction of Mn. When carried out in a cell with a lithium anode, this process occurs below 3 V, and the discharge profile is flat, indicative of a two-phase reaction. The tetragonally distorted phase $\text{Li}_2\text{Mn}_2\text{O}_4$ (space group $\text{I4}_1/\text{amd}$) is formed due to the cooperative Jahn–Teller effect, which occurs when more than half the manganese is in the form of d^4 Jahn–Teller Mn^{3+} ions. The phase transition results in a 16% increase in the c/a ratio [100] ($a = c = 8.248 \text{ \AA}$ in LiMn_2O_4 ; $a = 8.007 \text{ \AA}$, $c = 9.274 \text{ \AA}$ in $\text{Li}_2\text{Mn}_2\text{O}_4$). In theory, lithium cells containing LiMn_2O_4 can either be charged or discharged initially, and then cycled over a composition range of $0 \leq x \leq 2$ in $\text{Li}_x\text{Mn}_2\text{O}_4$ to give a total specific capacity of 285 mAh/g. Figure 5 shows the voltage profile of a Li/modified LiMn_2O_4 cell assembled in the author's laboratory, after discharging



Battery Cathodes. Figure 5

Discharge profile of a Li/modified- LiMn_2O_4 cell at 0.1 mA/cm^2 . Cell was initially discharged to 2 V and then charged to 4.3 V. This was the third discharge between 4.3 and 2.0 V

into the 3 V region and full recharge. Both 4 and 3 V plateaus are evident; although the overall capacity is somewhat lower than the theoretical value.

The large anisotropic volume change associated with formation of tetragonal $\text{Li}_2\text{Mn}_2\text{O}_4$ results in particle disintegration and loss of connection within the composite electrode. This causes such a rapid loss of capacity that, in practice, the cycle lives of cells containing LiMn_2O_4 discharged even a few times into the 3 V region are greatly compromised. In contrast, the extraction of lithium from LiMn_2O_4 above 4 V versus Li/Li^+ maintains the cubic structure and results in smaller volume changes. For this reason, discharge is typically limited to the 4 V plateau (Fig. 3), which exhibits much better reversibility. The theoretical capacity associated with this plateau is 148 mAh/g, although it is difficult to fully extract all the lithium, resulting in somewhat lower practical values.

From the early 1990s onward, intensive efforts were devoted to the development of LiMn_2O_4 for lithium-ion batteries, particularly at Bellcore Laboratories [101–103]. Although limiting discharges to the 4 V plateau resulted in much better cycling than when both the 3 and 4 V plateaus were utilized, gradual capacity fading was still observed [104]. This behavior was attributed to several factors, including irreversible side reactions with the electrolyte due to the high potential, loss of oxygen from the delithiated spinel, dissolution of Mn, and production of tetragonal $\text{Li}_2\text{Mn}_2\text{O}_4$ at particle surfaces, particularly at high discharge rates [100, 105].

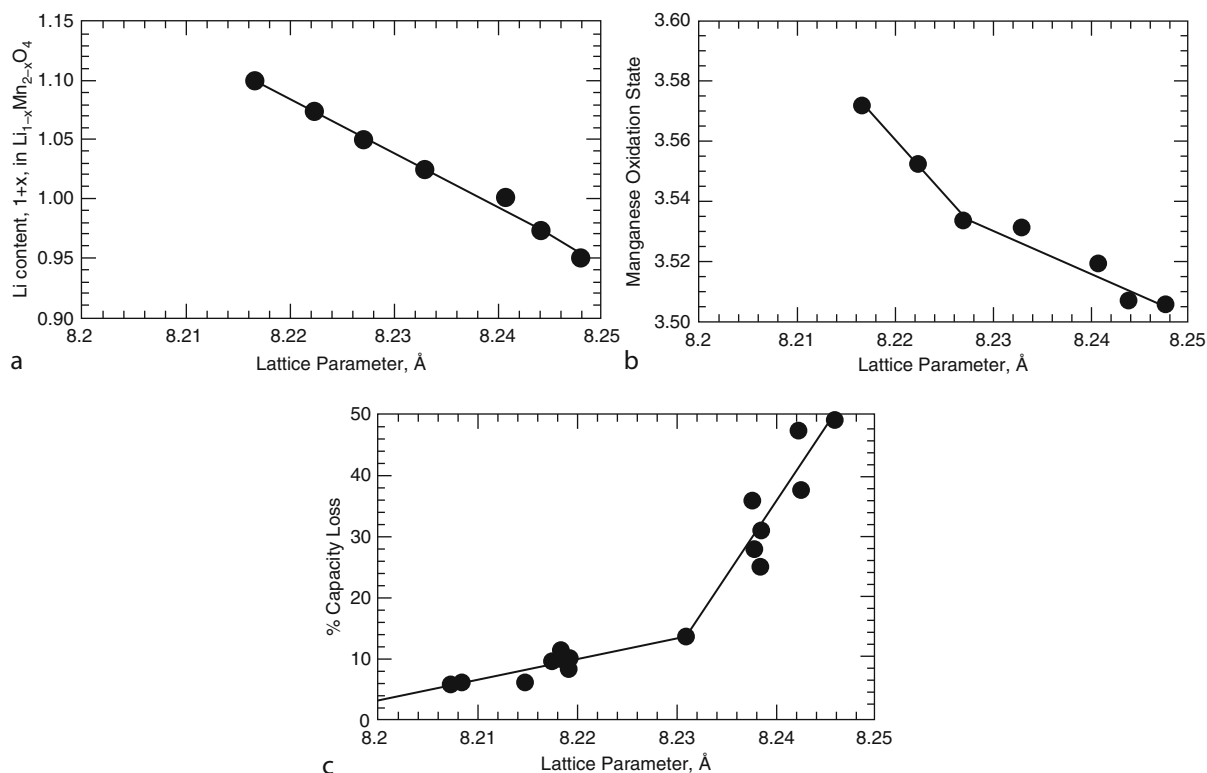
Partial substitution of Mn to form $\text{LiM}_x\text{Mn}_{2-x}\text{O}_4$ improves capacity retention [106–112]. Of particular interest are the lithium-substituted materials having the general formula $\text{Li}_{1+x}\text{Mn}_{2-x}\text{O}_4$. As lithium is substituted for manganese on the $16d$ sites (x is increased), the average oxidation state of the latter rises. This effectively decreases the 4 V capacity in proportion to the amount of substitution but results in a higher average oxidation state of the Mn at the end-of-discharge. This ameliorates the tendency to form the tetragonally distorted phase under nonequilibrium conditions such as rapid discharging, because this occurs only when the Mn oxidation state falls below an average of 3.5. Because Mn is fully oxidized before all the lithium can be extracted from $8a$ sites, side reactions are suppressed. Finally, dissolution of Mn

decreases because this phenomenon is dependent on the concentration of trivalent ions.

Li substitution and the attendant increase in Mn oxidation state in the as-made $\text{Li}_{1+x}\text{Mn}_{2-x}\text{O}_4$ compounds decrease the lattice parameter, a (Fig. 6a and b). The magnitude of this value correlates closely with the amount of capacity loss upon cycling (Fig. 6c), so that it can be used to predict the cycling behavior of the spinel materials [113]. In particular, improvements are most marked when $a \leq 8.23$ Å. Because the cycling behavior is so much better than LiMn_2O_4 , nearly all commercial manganese oxide spinel materials (LMOs) made today are lithium substituted. These have theoretical specific capacities of 100–120 mAh/g (Table 1), somewhat lower than that for LiMn_2O_4 .

The maximum possible substitution in $\text{Li}_{1+x}\text{Mn}_{2-x}\text{O}_4$ corresponds to $x = 1/3$ (the compound $\text{Li}_{4/3}\text{Mn}_{5/3}\text{O}_4$ or $\text{Li}_4\text{Mn}_5\text{O}_{12}$), at which point all of the Mn is in the +4 oxidation state and there is no 4 V capacity, because oxidative extraction of lithium cannot occur. Nevertheless, it is possible to insert lithium reversibly into octahedral $16c$ sites at about 2.9 V versus Li/Li^+ until a composition of $\text{Li}_7\text{Mn}_5\text{O}_{12}$ is reached, for a total of 156 mAh/g [114, 115]. The cubic symmetry is maintained until about $\text{Li}_{6.5}\text{Mn}_5\text{O}_{12}$, at which point Mn is reduced to an average oxidation state of 3.5 and the cooperative Jahn–Teller effect induces a tetragonal distortion. Because this process occurs only at the end-of-discharge, $\text{Li}_4\text{Mn}_5\text{O}_{12}$ exhibits much better cycling behavior on the 3 V plateau than does LiMn_2O_4 . However, the low operating voltage and capacity, and the inability to extract lithium makes $\text{Li}_4\text{Mn}_5\text{O}_{12}$ impractical for Li-ion batteries.

It is also possible to prepare cation-deficient or defect spinels, $\text{Li}_{1-x}\text{Mn}_{2-2x}\text{O}_4$ [114]. The cation vacancies increase the average oxidation state of Mn and decrease the capacity above 4 V in favor of that below 3 V, proportionally with x . In the end-member compound $\text{Li}_2\text{Mn}_4\text{O}_9$ (corresponding to $x = 0.11$ in $\text{Li}_{1-x}\text{Mn}_{2-2x}\text{O}_4$), all Mn is tetravalent, and lithium cannot be extracted, so that there is no capacity at 4 V. Lithium can be inserted below 3 V versus Li/Li^+ , to a maximum composition of $\text{Li}_5\text{Mn}_4\text{O}_9$. Although the theoretical capacity (213 mAh/g) is higher than that of $\text{Li}_4\text{Mn}_5\text{O}_{12}$, approximately 1/3 of it is associated with the formation of the Jahn–Teller distorted tetragonal phase.



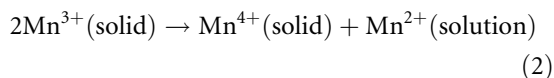
Battery Cathodes. Figure 6

(a) The variation of the lattice parameter, a , with the lithium content of $\text{Li}_{1+x}\text{Mn}_{2-x}\text{O}_4$; (b) the variation of lattice parameter with the average Mn oxidation state in $\text{Li}_{1+x}\text{Mn}_{2-x}\text{O}_4$; and (c) relationship between capacity loss after 120 cycles and the lattice parameter in $\text{Li}_{1+x}\text{Mn}_{2-x}\text{O}_4$ (Used with permission from Ref. [113])

In principle, defect spinels with values of $x < 0.11$ should cycle on the 4 V plateau better than LiMn_2O_4 for the same reasons as the lithium-rich stoichiometric spinels. In practice, it is difficult to control the degree of non-stoichiometry during synthesis, so these materials are not of interest commercially.

In spite of the improved performance exhibited by the lithium-substituted spinels, capacity fading upon cycling is still observed in electrochemical cells, particularly at elevated temperatures (55°C) [116–121]. This has negative implications particularly for vehicular applications, where batteries may be subjected to a wide variety of operating and storage conditions, including very warm environments. The dissolution is associated with Mn^{3+} disproportionation (Eq. 2) in the presence of acidic components of the

LiPF_6 /organic carbonate electrolyte solutions used in Li-ion batteries.



Loss of manganese leads to the formation of a defect spinel structure with reduced or no 4 V capacity [104, 116–121]. Additionally, proton exchange [116–121], phase separation, film formation, and precipitation of MnO and MnF_2 may occur, increasing cell impedance and exacerbating the capacity fading. More significantly, dissolved Mn^{2+} can cross over to the anode, become reduced, and precipitate as the metal, increasing the charge-transfer resistance and disrupting the critical SEI layer [122, 123]. The graphite anode is

markedly more sensitive to this effect than lithium is. Thus, assessment of spinel cathodes to determine the effectiveness of an approach to improve resistance to dissolution should ultimately be carried out in a full cell configuration rather than in lithium half-cells.

Some methods designed to address the problem of spinel dissolution include coating of particles [124, 125] and the use of new non-fluorinated salts such as lithium bis(oxalato)borate (LiBOB) which do not generate HF in situ [126–128]. Interestingly, dissolution of manganese appears to be suppressed in electrodes where LMO is mixed with an NMC [129]. Although the cycling behavior of Li-ion cells with spinel electrodes is still inferior to that of devices containing alternative commercial cathode materials (Table 2), other aspects of performance such as rate capability and safety [33–36, 130], the wide availability of manganese precursors, and the potential for low cost make LMO attractive especially for vehicular applications. Thus, at least one battery manufacturer focused on vehicle technologies (e.g., Enerdel, Indianapolis, IN) is pursuing the development of Li-ion batteries with spinel cathodes and hard carbon anodes (which are less sensitive to the effects of manganese dissolution than graphite).

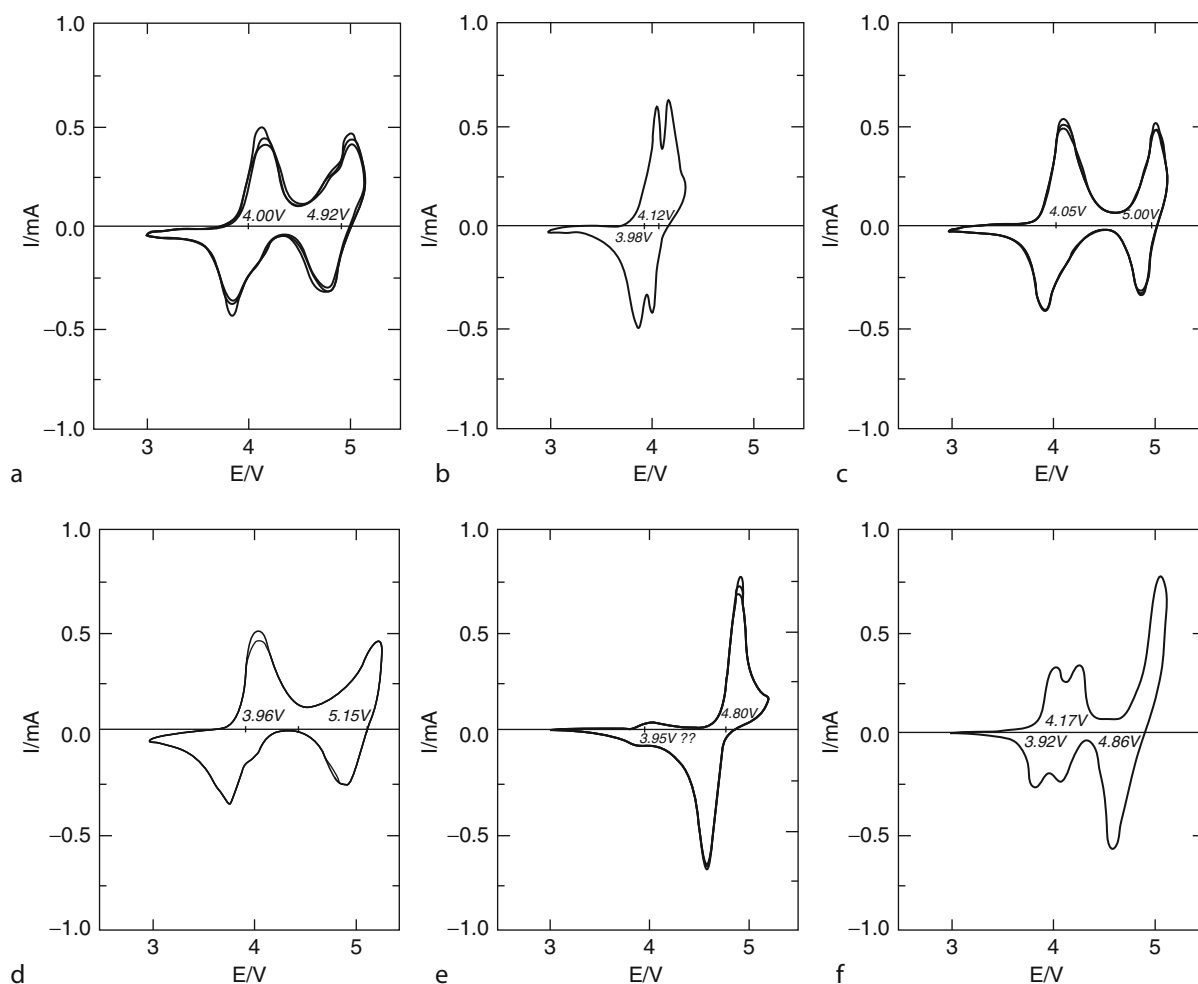
Several lithium-containing oxide spinels having transition metals other than Mn can also be synthesized. One example is LiCo_2O_4 , which can be prepared from a low-temperature form of LiCoO_2 [131]. (The latter, known as LT- LiCoO_2 , has a structure intermediate between that of a spinel and layered compound). Another is LiNi_2O_4 [25]. Unlike LiMn_2O_4 , the electrochemical characteristics of most of these spinels are inferior to those of the layered analogs, so that they are not of technological interest as cathode materials. However, $\text{Li}_4\text{Ti}_5\text{O}_{12}$ (LTO), which, because of its voltage properties, functions as an anode material, demonstrates excellent cycling performance. Although the energy density is lower than that of graphite, it does not require the formation of an SEI. Thus, it is also an attractive match for LMO cathode materials. Batteries with LTO anodes and LMO or other high-voltage cathodes may find utility in HEVs, which do not require as high an energy density as pure EVs.

The intensive search for substituted lithium manganese spinels with better cycling performance led to

the discovery of several materials having capacity near 5 V versus Li/Li^+ . These include spinels substituted with Cr, Fe, Cu, Co, or Ni [132–136]. In most cases, these materials exhibit a plateau near 4 V as well as a second plateau near 5 V, with the magnitude of the latter increasing with larger x in $\text{LiM}_x\text{Mn}_{2-x}\text{O}_4$ (where $M = \text{Cr, Fe, Cu, Co, or Ni}$). The 4 V capacity is associated with the usual $\text{Mn}^{3+}/\text{Mn}^{4+}$ spinel redox couple, whereas the higher voltage plateau is associated with redox processes of the substituting metal. Interestingly, the compound $\text{LiNi}_{1/2}\text{Mn}_{3/2}\text{O}_4$ has very little 4 V capacity, unlike other $\text{LiM}_{1/2}\text{Mn}_{3/2}\text{O}_4$ spinels [137] (Fig. 7).

In the case of $\text{LiNi}_{1/2}\text{Mn}_{3/2}\text{O}_4$, nearly all of the Mn is tetravalent [136], so that further oxidation is not possible. The specific capacity of 147 mAh/g at 4.7 V is associated with $\text{Ni}^{2+}/\text{Ni}^{4+}$ redox processes. The high energy density and high voltage makes this material attractive for vehicular applications, because fewer cells need to be connected in series to make the 300 V packs used in electric vehicles. This simplifies engineering, results in comparatively higher energy density on the system level because less hardware is required, and lowers costs. ETV Motors of Herzliya, Israel, is one company actively developing $\text{LiNi}_{1/2}\text{Mn}_{3/2}\text{O}_4$ batteries for this purpose.

The very high potential at which this cathode operates, however, presents considerable challenges for cycle life. Although conventional carbonate-based electrolytes used in Li-ion batteries have, in principle, excellent oxidative stability, the presence of impurities such as water may contribute to side reactions that decrease resistance to irreversible oxidation, resulting in shortened battery lifetimes. In addition, cell components such as carbon additives used to improve conductivity in composite cathodes, or surfactants that aid in wetting may oxidize irreversibly at high potentials, and current collectors may corrode. Thus, cycling is usually restricted to a voltage range below about 4.3 V versus Li/Li^+ (4.2 V in cells with graphite anodes). Stringent purification of electrolytes and the use of special protective additives are allowing gradual extension of this range. In addition, the development of new electrolytes containing ionic liquids or sulfolanes is expected to enable high-voltage cell operation, although the choice of anode may then be restricted



Battery Cathodes. Figure 7

Slow-scan voltammetry of $\text{Li}/\text{LiMn}_{1/2}\text{Mn}_{3/2}\text{O}_4$ cells with $M =$ (a) Cr, (b) Mn, (c) Fe, (d) Co, (e) Ni, and (f) Cu at a rate of 0.2 mV/s using 1 M LiPF_6 in 1:1 v/v EC/DEC electrolyte (Used with permission from Ref. [137])

to LTO or other materials that do not require SEI formation. Other strategies to prolong the cycle life of cells containing $\text{LiNi}_{1/2}\text{Mn}_{3/2}\text{O}_4$ include treating active material particles with protective coatings to minimize direct contact with electrolyte solutions [138–140], or partial substitution of Ni or Mn with other cations such as Ti, Mg, or Zn [141–143].

Synthesis of $\text{LiNi}_{1/2}\text{Mn}_{3/2}\text{O}_4$ is normally carried out at high temperatures to ensure good crystallinity and to lower the surface area and thus minimize reactivity with electrolyte solutions and other components. Under these conditions, oxygen loss may occur, leading to the formation of a non-stoichiometric material

($\text{LiNi}_{1/2}\text{Mn}_{3/2}\text{O}_{4-x}$) containing some Mn^{3+} in the structure. Additionally, a rock salt impurity, $\text{Li}_x\text{Ni}_{1-x}\text{O}$, is also produced. Annealing at 700°C partially reverses the oxygen loss, but the telltale 4 V capacity indicative of the presence of electroactive Mn^{3+} can often be observed in cells made with these materials (e.g., in Fig. 7e). Substitution with other metals, as discussed in the papers listed in Refs. [141–143], often decreases the amount of Mn^{3+} in these compounds, which may play a role in the observed improvements in cycling.

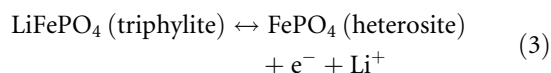
If the sample is cooled slowly during synthesis, an ordered phase can be produced (space group $P4_332$ with Ni in $4b$ sites and Mn in $12d$ sites [144]). The

electrochemical properties (in particular, rate capability) of the ordered phase are inferior to those of the disordered non-stoichiometric phase [145, 146]. The mixed Mn valency in the disordered Fd-3m phase leads to an increase in the electronic conductivity of about 1.5 orders of magnitude compared to that of the ordered material. This is thought to be responsible for the increased rate capability of the former compared to the latter.

The presence of electroactive Mn in disordered $\text{LiNi}_{1/2}\text{Mn}_{3/2}\text{O}_4$ suggests that dissolution may be problematic, as it is with the LiMn_2O_4 variants. In spite of this and the high operating voltages, extremely stable cycling has been observed in full cell configurations, albeit with $\text{Li}_4\text{Ti}_5\text{O}_{12}$ anodes [147].

LiFePO₄ and Other Phospho-olivines

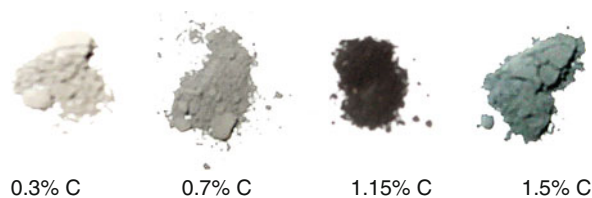
In 1997, Goodenough and coworkers reported on the electrochemical properties of a new class of cathode materials known as the phospho-olivines [148], which adopt the orthorhombic structure (space group Pnma) shown in Fig. 2c. In the case of LiFePO_4 (triphylite), Li^+ and Fe^{2+} occupy octahedral sites, and P is located in tetrahedral sites in a somewhat distorted hexagonal close-packed (hcp) oxygen array. The FeO_6 octahedra share corners and LiO_6 octahedra share edges along tunnels down the *b*-axis, through which the Li ions can diffuse. Extraction and reinsertion of Li from LiFePO_4 proceeds at about 3.45 V in a lithium cell with a theoretical specific capacity of 170 mAh/g. The potential is independent of the composition *x* in Li_xFePO_4 (i.e., the voltage profile is flat, Fig. 3) indicating that a two-phase reaction occurs. In situ X-ray diffraction and Mossbauer experiments on Li/LiFePO₄ cells [149] show that the two relevant phases are triphylite and FePO_4 , also known as heterosite (Eq. 3).



Initial reports on the electrochemical characteristics of LiFePO_4 emphasized its poor rate capability and the lower than expected utilization in lithium cells even when discharged at low current densities (e.g., only about 60% in Ref. [149]). This was attributed to the low electronic conductivities of both the triphylite and heterosite phases [150]. Coating particles with carbon

ameliorates the low conductivity and result in better rate performance [151]. This is most conveniently achieved by including a carbon source during initial synthesis of the LiFePO_4 sample. The presence of carbon or carbon-containing precursors during calcination in an inert atmosphere has several additional beneficial effects; it retards grain growth, resulting in small particles that allow rapid extraction of Li ions, and prevents formation of Fe^{3+} -containing impurities. It also allows the use of easy-to-handle, low-cost, Fe^{3+} -containing starting materials such as iron nitrate, which are reduced during the heating process [152].

In practice, many lab-synthesized samples of LiFePO_4 contain carbon, due to the use of precursors such as iron oxalate [153]. Even small amounts of carbon can result in drastic sample color changes from the off-white of native LiFePO_4 (Fig. 8). The electrochemical performance is also greatly affected by the carbon content, although this also depends on the distribution of carbon over particle surfaces and details of its structure [154–157]. Carbons produced in situ during synthesis of LiFePO_4 are disordered due to the relatively low calcination temperatures (generally, 600–700°C). Disordered carbons are less conductive than graphite, and conductivity depends on the size and number of graphene domains. The use of graphitization catalysts (often containing iron) improves the conductivity of coatings by several orders of magnitude, and can also result in co-production of carbon nanotubes or fibers, which wire particles together [158, 159]. The result is that very small amounts of carbon, often less than 2 wt.%, are sufficient to produce high-rate LiFePO_4 samples. This is important because too much lightweight carbon adversely affects the tap densities of LiFePO_4 composites, further decreasing the already somewhat low energy density [160].



Battery Cathodes. Figure 8

Photographs of LiFePO_4 samples containing varying amounts of carbon (Used with permission from Ref. [153])

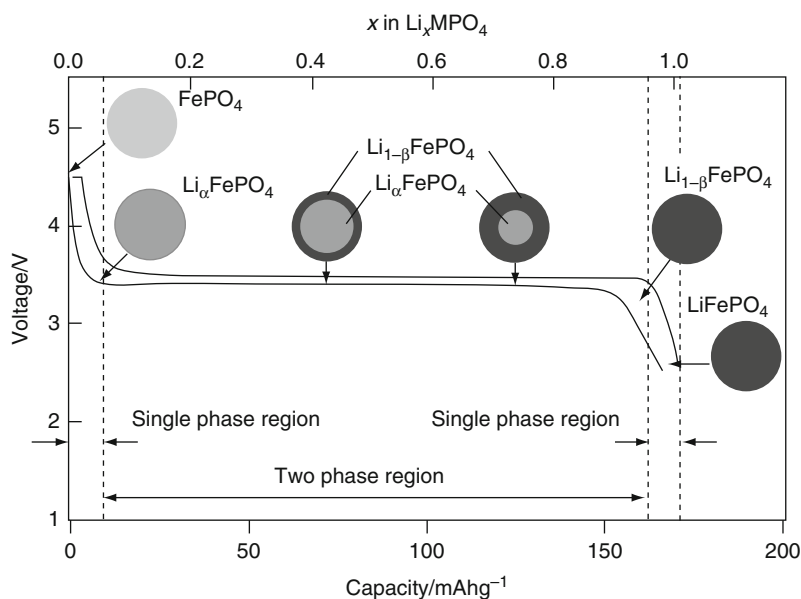
The changes in sample color, increases in bulk conductivities, and improved electrochemical performance induced by the presence of very small amounts of carbon (or other highly colored impurities) complicate the interpretation of results of doping experiments intended to increase the intrinsic conductivity of LiFePO_4 . A color change from off-white to black or gray should not be regarded as proof-positive of successful doping and increased intrinsic electronic conductivity, for the reasons described above. Even when carbonaceous precursors are not used, the use of organic solvents or plastic containers during grinding or other processing steps may introduce carbon. Early claims of successful low-level aliovalent substitution [161] on the Li sites of LiFePO_4 , resulting in greatly enhanced conductivities and electrochemical performance, may have been a fortuitous consequence of well-distributed electronically conductive impurities such as carbon and metal-rich phosphides [162–166]. Recent studies of the defect chemistry of LiFePO_4 show that substitution of multivalent ions on the Li site is very limited, and always accompanied by lithium vacancies, so that no mixed valency for iron occurs [167]. Earlier computational modeling of the defect, dopant, and Li transport properties of LiFePO_4 [168] indicates that substitution of multivalent ions on Li or Fe sites (other than divalent ions on the latter) is not energetically favored. It was predicted that the most likely type of defect is the Li-Fe anti-site pair, in which Li^+ ions are located on Fe^{2+} sites and are balanced by an equal number of Fe^{2+} ions on Li sites. Recent work, however, shows that there is a marked asymmetry between the number of Fe ions on Li sites and vice versa [169–171]. Very few lithium atoms can be accommodated on iron sites. More commonly, Fe ions on Li sites are accompanied by a small number of vacancies, to form $[\text{Li}_{1-2x}\text{Fe}_x]\text{FePO}_4$. The presence of relatively immobile multivalent ions on Li sites interferes with fast Li diffusion, since LiFePO_4 is essentially a one-dimensional ion conductor [172–174]. Likewise, a large number of anti-site defects are likely to impact electrochemical performance adversely [175, 176] as is seen in Refs. [169–171]. At any rate, it is apparent that near room temperature, only a relatively small concentration of vacancies or interstitial defects is possible.

Carbon coatings, although convenient for the reasons stated above, are not absolutely necessary to assure good electrochemical performance [177], as long as particle sizes are kept small and particle size distributions are narrow. Nanostructuring reduces diffusion distances and ameliorates the effects of low electronic conductivity, allowing full discharge at even moderate to high rates. Subtle changes in the discharge characteristics of LiFePO_4 samples occur as particle size is decreased, most notably, a stronger dependence of voltage upon composition (x in Li_xFePO_4) close to the end-of-charge and end-of-discharge, implying solid-solution behavior [178, 179]. Other researchers have observed XRD, neutron diffraction, and electrochemical evidence of a small degree of lithium non-stoichiometry in larger Li_xFePO_4 particles at both composition extremes [180, 181], as illustrated in Fig. 9.

The existence of a small degree of non-stoichiometry (and thus mixed valence states for iron) may explain why this system is electroactive, given that both end members have such poor electronic conductivity. It should be noted, however, that kinetic effects, surface impurities, and the presence of defects [179, 182–184] also influence the shape of the Li/ LiFePO_4 discharge profile. This makes it hard to determine what the exact compositional ranges of solid-solution behavior are at room temperature from the electrochemical data alone. Complications from the effects of strain also make the interpretation of diffraction data difficult.

Experiments conducted on heated $\text{LiFePO}_4/\text{FePO}_4$ mixtures of varying concentrations [185, 186] show that solid solutions form from $0 \leq x \leq 1$ in Li_xFePO_4 at elevated temperatures, however. A representative phase diagram is shown in Fig. 10. The solubility limits of lithium in heterosite and vacancies in triphylite are approximated in the figure, because of the uncertainties outlined above. Additionally, due to slow kinetics, the exact temperature boundaries are not known, explaining the differences observed by various researchers. Depending upon the initial concentration, and details of the crystal sizes and morphologies, metastable lithium-deficient phases can persist for remarkably long times after cooling [187].

The mechanism of the $\text{LiFePO}_4/\text{FePO}_4$ electrochemical reaction has been described using a shrinking



Battery Cathodes. Figure 9

Scheme of the discharge processes of Li_xFePO_4 , showing solid-solution behavior close to $x = 0$ and $x = 1$ (Used with permission from Ref. [180])

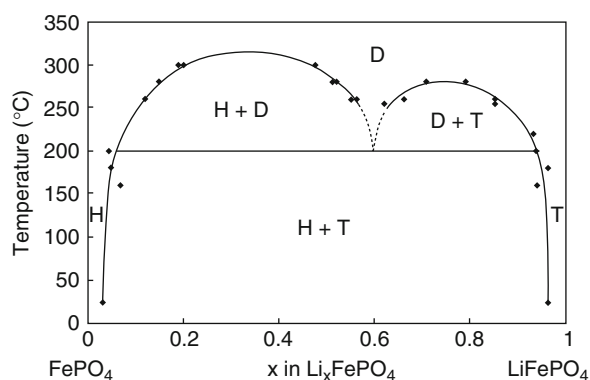
core model [188], as depicted in Fig. 9. During discharge, lithium initially inserts into FePO_4 to form the solid-solution $\text{Li}_\alpha\text{FePO}_4$ phase, where α is close to 0. Upon further passage of current, a shell of a lithium-rich material ($\text{Li}_{1-\beta}\text{FePO}_4$) is produced on the surface, over a core of $\text{Li}_\alpha\text{FePO}_4$. As the reaction continues to progress, the shell grows at the expense of the core, and the interface between the two phases shrinks, until complete conversion to $\text{Li}_{1-\beta}\text{FePO}_4$ occurs. Further lithiation produces LiFePO_4 at the end-of-discharge. The entire process is reversed upon charge. The anisotropy of lithium diffusion in LiFePO_4 [172–174], however, complicates the interpretation of the shrinking core model. A transmission electron microscopy (TEM) study of partially delithiated large plate-like particles [189] show that ordered domains of FePO_4 and LiFePO_4 alternate in the ac plane, separated by narrow disordered (but not amorphous) regions, where lithium mobility is enhanced. The phase transformation proceeds in the direction of the a -axis at dislocation lines that run parallel to the c -axis, consistent with one-dimensional Li^+ diffusion in the b -direction (Fig. 11). This somewhat resembles an early “mosaic” model proposed by Andersson et al. as

an alternative to the shrinking core model [190]. These observations also suggest that the best rate performance can be achieved with particles that are thin in the direction of Li diffusion (b -axis), but that nanostructuring in other directions may not be required.

In another recent study [191] using high-resolution electron energy loss spectroscopy (EELS) on a chemically prepared sample, a different distribution of the two phases in a partially delithiated particle was observed. In this case, LiFePO_4 was present only at the edges with FePO_4 located in the interior (but not on surfaces of the ac planes) of plate-like particles significantly smaller than those studied in Ref. [189]. This is consistent with a progressive emptying or filling of Li channels oriented along the b -axis, with the front between the two phases moving perpendicular to the ac plane. No disordered regions at the phase boundaries were detected, however. This lack of evidence for solid-solution behavior argues against a shrinking core mechanism, which requires that at least a small degree of non-stoichiometry exist in the system.

Variations in particle sizes and morphologies, as well as in the concentration of defects, may well

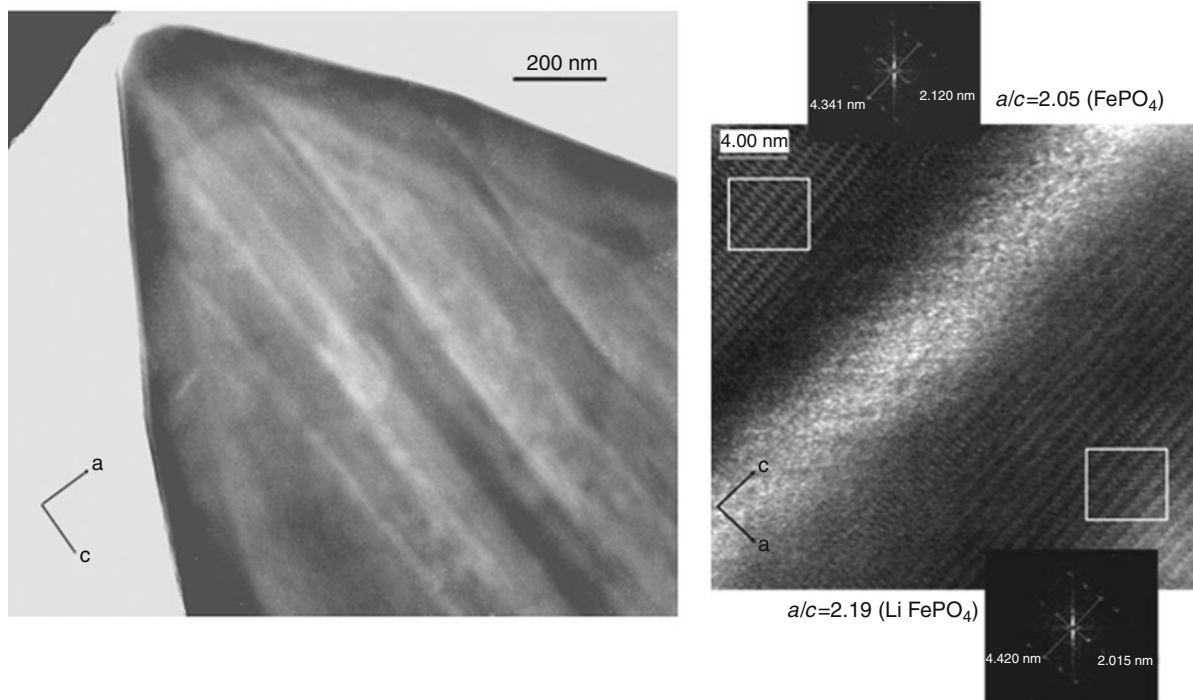
influence the progression of the delithiation reaction during chemical oxidation and explain these differing results. In electrochemical cells with composite



Battery Cathodes. Figure 10

Phase diagram of the Li_xPO_4 system, where T, H, and D denote triphylite, heterosite, and disordered (but not amorphous) phases, respectively (Used with permission from Ref. [186])

electrodes, the reaction may nucleate preferentially at sites where contact with conductive carbon additives or coatings and the electrolyte solution is the closest, leading to a different pattern of phase distributions than is seen in the chemically delithiated samples, where nucleation can occur at numerous sites simultaneously. In partially delithiated Li_xFePO_4 samples recovered from electrochemical cells, no mixed-phase nanoparticles were observed, leading the researchers to surmise that the reaction front propagates much more rapidly than nucleation [192]. A recent kinetic study also indicates that the $\text{LiFePO}_4/\text{FePO}_4$ transformation is controlled by a phase-boundary reaction [193]. However, newly discovered evidence of intercrystallite ionic transport, leading to a redox reaction between delithiated and lithiated particles and subsequent equilibration [194] complicates the interpretation of these results. Moreover, areas of composite electrodes with poor electronic connectivity may be electrochemically inactive, leading to islands of unreacted LiFePO_4 .



Battery Cathodes. Figure 11

Left: TEM image showing a partially delithiated crystal with the global composition $\text{Li}_{0.5}\text{FePO}_4$, showing domains of LiFePO_4 and FePO_4 aligned along the c -axis. Right: High-resolution TEM image with Fourier transforms of the boxed areas, identifying the two phases (Used with permission from Ref. [189])

In that case, all of the lithium will be extracted from LiFePO_4 in better connected areas, and mixtures of FePO_4 and LiFePO_4 will be observed, as in Ref. [192].

While the actual mechanism of the $\text{LiFePO}_4/\text{FePO}_4$ transformation remains a subject of debate, it seems clear that the shrinking core model does not apply to the primary particles themselves. The model may, however, still be applicable on a larger scale, for example, to the secondary particles comprised of agglomerates.

Over the past decade, better control of synthesis parameters, the use of conductive coatings, and nanostructuring have transformed LiFePO_4 from a poorly performing material to one of the most attractive cathodes for Li-ion batteries. LiFePO_4 appears to be particularly well suited to high-power applications including power tools and vehicle propulsion. A recent study shows that extraordinarily high charge and discharge currents can be sustained in cells designed so that a modified LiFePO_4 limits rate [195]. (While these devices are not practical for real-world use, they serve to demonstrate the intrinsic rate capability of LiFePO_4 without interference from mass transfer limitations in other cell components). There have been reports [196, 197] of iron dissolution in LiPF_6 -containing electrolytes leading to capacity fading at elevated temperatures (analogous to the problems observed with manganese oxide spinels), although this may be due to the presence of iron-containing surface impurities such as Fe_2P rather than to the LiFePO_4 itself. The thermal properties of the $\text{LiFePO}_4/\text{FePO}_4$ system are a particularly attractive feature, leading to enhanced safety (LFP, Table 2). Upon heating, FePO_4 produced by charging LiFePO_4 transforms to the thermodynamically favored trigonal form (α -quartz structure). While this reaction is irreversible and leads to loss of capacity, it progresses without evolution of oxygen [198]. This is in contrast to transition metal oxides, all of which lose oxygen to some degree at high states-of-charge. This makes this cathode especially appealing for traction applications, where safety is paramount.

Because LiFePO_4 is less dense than the layered oxides or spinels (the crystallographic density is 3.6 g/cm^3 compared to about 5 g/cm^3 for the oxides), and the potential versus lithium is lower, the energy density is less than that of the oxides (Table 2). The specific energy, in contrast, is competitive with LMO (Table 1), but for many applications, the energy per

unit volume matters more than per weight. The discharge potential of the isostructural LiMnPO_4 is about 0.5 V versus Li/Li^+ higher than that of LiFePO_4 [199], which increases the specific energy by about 15%. Unfortunately, this material is even less dense than LiFePO_4 (3.4 g/cm^3), and the conductivity appears to be several orders of magnitude lower [200, 201]. Synthetic procedures used to produce nanoparticulate LiMnPO_4 and variants include sol-gel, precipitation, combustion techniques, spray pyrolysis, and hydrothermal or solvothermal (polyol process) methods [176, 202–208]. For samples calcined in air for the sake of convenience, a fair amount of carbon is generally added after synthesis to offset the low conductivity. Coating can also be achieved via incorporation of carbonaceous precursors or elemental carbon during heat treatment under inert atmosphere, as with LiFePO_4 . Electrochemical performance improves as the average primary particle size decreases [209]. Partial Mg substitution on the Mn site is also beneficial [208, 210–212]. This effect has been attributed to stabilization against strain associated with the Jahn–Teller distortion of Mn^{3+} ions in the delithiated phase, as well as decreased volume changes upon cycling. The best results reported so far have been for solvothermally prepared powders (polyol process) embedded in a carbon matrix [213]. Still, the rate capability of LiMnPO_4 is not as impressive as that of LiFePO_4 , and many of the strategies employed to improve the electrochemistry (Mg substitution, addition of large amounts of carbon, nanostructuring) reduce the already fairly small energy density advantage. The disappointing performance has been variously attributed to poor transport properties in either the bulk LiMnPO_4 or MnPO_4 phases, the instability of the MnPO_4 phase itself, or surface effects [201, 214, 215]. While the voltage profile of LiMnPO_4 is flat during charge and discharge, indicating a two-phase process, evidence of solid-solution behavior near the MnPO_4 limit has been observed [216]. As with the $\text{LiFePO}_4/\text{FePO}_4$ system, the non stoichiometry may enable the electrochemical activity. However, no solid-solution behavior near the LiMnPO_4 end of the phase diagram has yet been detected.

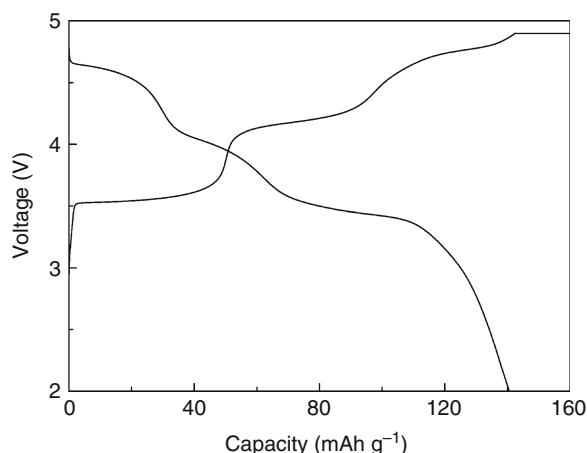
Although the performance characteristics of the $\text{LiMnPO}_4/\text{MnPO}_4$ system may improve with further work, one troubling aspect of this electrode is its

thermal instability in the charged state. Unlike LiFePO_4 , MnPO_4 evolves oxygen gas upon heating to 200°C and decomposes to form $\text{Mn}_2\text{P}_2\text{O}_7$ [217, 218]. The instability of MnPO_4 is probably related to the strong Jahn–Teller distortion of the Mn^{3+} ion. LiMnPO_4 is therefore less attractive than LiFePO_4 in terms of safety, and does not have better performance characteristics than the metal oxides. Charging is also somewhat problematic, because high over-potentials are required due to the kinetic limitations. Thus, it seems unlikely that this cathode material will prove useful for traction batteries in the near term, although other applications may be feasible.

Phospho-olivine compounds containing Co or Ni also exist. LiCoPO_4 exhibits electrochemical activity at about 4.8 V versus Li/Li^+ [219, 220]. LiNiPO_4 is predicted to discharge at about 5.1 V in a lithium cell, but appears to be nearly completely inactive [221]. Neither of these is likely to be used as cathodes for lithium-ion batteries in the near term in part because of the very high voltages needed to charge the materials, which present a number of practical problems.

Solid solutions containing a mixture of transition metals can be prepared over a wide composition range [176]. $\text{Li}[\text{Mn}_y\text{Fe}_{1-y}]\text{PO}_4$ compounds exhibit two plateaus in the discharge profile at about 4.1 and 3.45 V versus Li/Li^+ with their relative magnitudes proportional to the amounts of Mn and Fe, respectively [148]. In general, for $y < 0.8$, the mixed metal phospho-olivines appear to undergo more facile electrochemical reactions than the pure end-member phase, LiMnPO_4 [215, 222]. A study of the delithiation reactions of these phases [223] suggested that the system is single phase when $x < 1 - y$, but biphasic over the 4.1 V plateau (corresponding to the $\text{Mn}^{2+}/\text{Mn}^{3+}$ redox couple). A later synchrotron diffraction study [224] showed two two-phase regions roughly coinciding with the two plateaus and a narrow solid-solution region between $x = 0.55$ and 0.67 for $\text{Li}_x\text{Mn}_{0.6}\text{Fe}_{0.4}\text{PO}_4$, $_x\text{Mn}_{0.6}\text{Fe}_{0.4}\text{PO}_4$, corresponding to the steeply sloping portion of the discharge profile between the plateaus.

Other mixed transition metal phospho-olivines have been prepared containing Ni and Co [220] and Fe, Mn, and Co [225–227]. In the case of the $\text{Li}[\text{Ni}_y\text{Co}_{1-y}]\text{PO}_4$, only one plateau was observed at 4.8 V, corresponding to the $\text{Co}^{2+}/\text{Co}^{3+}$ redox couple. The only effect of the Ni substitution is to reduce the



Battery Cathodes. Figure 12

Charge and discharge of a $\text{Li}/\text{LiMn}_{1/3}\text{Fe}_{1/3}\text{Co}_{1/3}\text{PO}_4$ cell, showing three distinct plateaus corresponding to the redox of Co (4.8 V), Mn (4.1 V), and Fe (3.45 V) (Used with permission from Refs. [225–227])

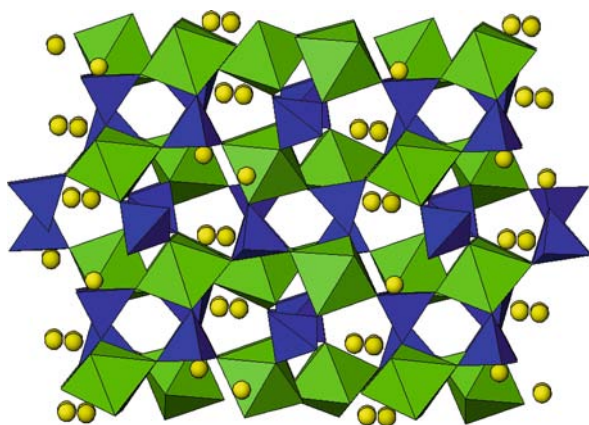
overall capacity, demonstrating the poor electro-activity of Ni in the phospho-olivine structure. In lithium cells containing $\text{LiMn}_{1/3}\text{Fe}_{1/3}\text{Co}_{1/3}\text{PO}_4$, on the other hand, three distinct electrochemical features are observed, corresponding to redox processes of the three types of transition metals (Fig. 12). Interestingly, the reaction appears to be single phase over the entire composition range, $0 \leq x \leq 1$ in $\text{LiMn}_{1/3}\text{Fe}_{1/3}\text{Co}_{1/3}\text{PO}_4$, and the redox potentials of the $\text{Fe}^{2+}/\text{Fe}^{3+}$ and $\text{Co}^{2+}/\text{Co}^{3+}$ couples are slightly shifted compared to the corresponding LiMPO_4 electrodes containing only one metal. The manganese redox processes appear to be more sluggish than those of iron and cobalt, and at higher discharge rates, the electrochemical feature at 4.1 V disappears. Tailoring of the voltage profile by incorporating multiple metals in the olivine structure may have practical use as a state-of-charge indicator for vehicular batteries (acting much like the gas gauge in conventional combustion engine automobiles).

Other Phosphates and Poly-anionic Compounds

There are many other transition metal-containing poly-anionic compounds with structures amenable to lithium insertion processes. Among these are numerous materials with the Nasicon structure

(Nasicon stands for sodium superionic conductor and originally referred to $\text{Na}_{1+x}\text{Zr}_2\text{P}_{3-y}\text{Si}_y\text{O}_{12}$ compounds [228]). These have the general formula $\text{A}_x\text{M}_2(\text{XO}_4)_3$, where A is an alkali metal or alkaline earth, M is a transition metal or combination of transition metals, and X is P, As, Si, or S or a combination of these. M is octahedrally coordinated by oxygen, and X is tetrahedrally coordinated. All corners of the XO_4 tetrahedra are shared with MO_6 octahedra and vice versa; these link to form open channels in which the alkali or alkaline earth ions are located. There are also closely related three-dimensional framework structures with differing arrangements of corner-sharing polyhedra and distributions of alkali metal cations, such as the monoclinic $\text{Li}_3\text{Fe}_2(\text{PO}_4)_3$ shown in Fig. 13.

Transport of alkali metal ions through the tunnels in Nasicons can be extremely rapid, particularly at elevated temperatures, although the electronic conductivities are low. For these reasons, these materials were originally proposed for use as solid ionic conductors (e.g., to replace β'' alumina in high temperature Na/S batteries). In spite of their low electronic conductivities, researchers recognized that Nasicon structures with redox-active transition metals and related three-dimensional framework compounds could function as electrode materials as early as the late 1980s [229–231] and numerous materials were investigated [232, 233]. In many cases, the electrochemical properties are



Battery Cathodes. Figure 13

The structure of monoclinic $\text{Li}_3\text{Fe}_2(\text{PO}_4)_3$ looking down the unique axis. P is located in the blue tetrahedra, and Fe in the green octahedra. Li ions are represented as spheres

unsuitable for Li-ion batteries. For example, Li cannot be extracted from monoclinic $\text{Li}_3\text{Fe}_2(\text{PO}_4)_3$, only inserted, and the discharge occurs at a rather low voltage (2.8 V versus Li/Li^+). In contrast, up to two lithiums per formula unit can be extracted reversibly from monoclinic $\text{Li}_3\text{V}_2(\text{PO}_4)_3$, corresponding to a capacity of about 130 mAh/g at an average potential of 3.8 V [234–236]. Complex multiphasic behavior is exhibited upon redox, resulting in multiple plateaus in the discharge profile. In spite of significant volume changes upon lithium insertion and extraction, the material shows very good cycling behavior.

Fluorophosphates are relatively rare, but have recently been studied for Li-ion applications. The lithium in LiVPO_4F [237–239] can be extracted reversibly at a potential of about 4.2 V versus Li/Li^+ . Interestingly, lithium can also be inserted at about 1.8 V. Thus, a graphite-free lithium-ion battery can be built, using LiVPO_4F as both the anode and the cathode! $\text{Na}_3\text{V}_2(\text{PO}_4)_2\text{F}_3$ [240], $\text{Na}_2\text{FePO}_4\text{F}$ [241], and LiFePO_4F [242, 243] have also been investigated. The first two compounds were used as-is in electrochemical cells, and underwent ion exchange in situ. Although these cathodes eventually stabilize when used in lithium metal cell configurations and the cycling behavior is good, the presence of sodium in full cells with graphite anodes may disrupt the SEI layer and is therefore undesirable. Thus, these compounds will have to be ion-exchanged prior to use. In the case of LiFePO_4F , the investigators saw some evidence that a small amount of lithium could be extracted (with concomitant oxidation of Fe^{3+} to Fe^{4+}), but the main electrochemical reaction was insertion of lithium and reduction of Fe^{3+} to Fe^{2+} .

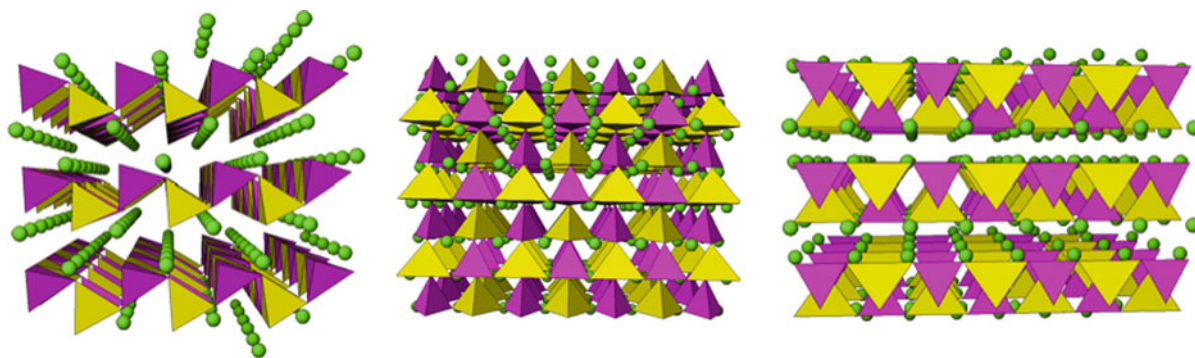
Other electroactive phosphorus-containing compounds include iron(III) hydroxyl phosphates with lipscombite or tavorite structures [244, 245], β - and ϵ - VOPO_4 [246–248], and LiVP_2O_7 [249]. Although the Nasicons, three-dimensional framework structures, and the aforementioned phosphates and diphosphates all have interesting electrochemical properties, most are not competitive with LiFePO_4 or the commercialized metal oxides for a variety of reasons. The iron-containing materials generally discharge at too low a voltage for use in Li-ion battery configurations and many have fairly low capacities. Some would need to be lithiated prior to use. The vanadium-containing

materials cycle well, and have sufficiently high voltages and capacities to ensure high energy density, but raise concerns about toxicity and environmental impact.

Interest has also recently been directed toward a family of silicates with the general composition Li_2MSiO_4 , where M is a divalent cation such as Fe^{2+} , Mn^{2+} , and Co^{2+} or a combination of these [250–257]. The chemical formula implies that it may be possible to extract two Li ions per transition metal unit, giving a very high theoretical specific capacity of about 330 mAh/g. These materials adopt structures in which Li, Si, and the transition metal ions all occupy tetrahedral sites in a distorted close-packed oxygen array. The particular polymorph obtained depends upon the nature of the transition metal as well as the temperature and method of preparation. In the β -polymorphs (low-temperature forms), the tetrahedra share only corners, and all point in the same direction. In γ -polymorphs (high temperature forms), triads of tetrahedra are arranged so that the central one points in the opposite direction and shares edges with the two outer tetrahedra. Numerous tetrahedral structures exist, with different ordering of the ions and varying degrees of distortion. Several different views of an electroactive β -polymorph (space group $\text{Pmn}2_1$) are shown in Fig. 14, which illustrates its quasi-layered nature. Accurate structure determination of these phases is complicated by the presence of impurities in many preparations and variations in synthetic procedures, which may lead to subtle structural differences [256, 258].

About one Li^+ per formula unit can be extracted from $\text{Li}_2\text{FeSiO}_4$ in electrochemical cells at low current densities and at 60°C [250, 251]. The initial extraction takes place at about 3.1 V versus Li/Li^+ , but subsequent discharges and charges occur at 2.8 V. This indicates that a structural change takes place, the exact nature of which is not entirely clear. After this initial change, however, relatively good cycling is observed, with an overall capacity of about 130 mAh/g (corresponding to somewhat less than 1 Li^+ per $\text{Li}_2\text{FeSiO}_4$). There is no experimental evidence that more than one Li^+ can be extracted, and first principle calculations indicate that it is not possible to do so at potentials compatible with conventional organic liquid electrolytes [259].

The differences between the potentials at which the first and second lithium ions can be extracted are much smaller when $\text{M}=\text{Mn}$, Co , or Ni in Li_2MSiO_4 than when it is Fe , however. As with the olivine system, the redox potentials for $\text{Li}_2\text{MnSiO}_4$ electrochemical processes (at least for extraction of the first lithium) are expected to be within the oxidative stability limits of organic electrolytes, while those of $\text{Li}_2\text{CoSiO}_4$ and $\text{Li}_2\text{NiSiO}_4$ are probably not. However the electrochemical behavior of $\text{Li}_2\text{MnSiO}_4$ appears to be much worse than that of $\text{Li}_2\text{FeSiO}_4$ [251, 254]. Belharaouk et al. [253] were able to achieve initial discharge capacities of about 135 mAh/g at room temperature, over a wide voltage range, by using carbon-coated submicron-sized particles, but this is still far less than predicted for complete extraction of all the lithium. Discharge capacities as high as about 250 mAh/g, however, can be obtained when



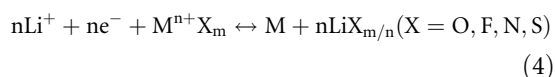
Battery Cathodes. Figure 14

Views of a β -polymorph of Li_2MSiO_4 looking down the a -axis (left), the b -axis (middle), and the c -axis (right). MO_4 (yellow) and SiO_4 (pink) tetrahedra alternate and connect to form layers through which lithium ions (green spheres) can diffuse

mixed metal compounds $\text{Li}_2\text{Mn}_x\text{Fe}_{1-x}\text{SiO}_4$ [252, 256] are used as cathodes in lithium cells. Unfortunately, the quality of the energy obtained is poor because the voltage profiles are steeply sloping over a range of about 4.5–1.0 V versus Li/Li^+ . At such low potentials, relatively little power can be obtained from the electrode. The extreme slope may be partly due to the severe kinetic and electronic limitations of the materials, leading to large over-potentials in lithium cells. If so, a combination of the carbon-coating and nanostructuring strategies used to improve the olivines may ameliorate the poor voltage characteristics and lead to new cathodes with nearly double the energy currently available.

Conversion Electrodes

A different class of electrode materials is based not upon insertion processes but on the displacement reactions of binary metal compounds [260, 261] (Eq. 4):



Conversion electrodes have long been used in primary systems (e.g., Li/CF_x batteries), but have only been proposed for use in rechargeable devices recently, when it was recognized that the reactions could be made reversible for nanoparticulate materials. While the specific capacities can be enormous, the voltage characteristics make most of these electrodes more suitable for use as anodes rather than as cathodes. A notable exception seems to be that of metal fluorides, which are electroactive anywhere from 2 to 4 V versus Li/Li^+ , depending on the identity of the metal, with specific capacities as high as 600 mAh/g. It is typical of conversion electrodes to exhibit significant hysteresis upon recharge, which may be intrinsic to the materials and processes. The mechanisms of conversion reactions are complex and involve bond breaking and considerable rearrangement, unlike that of insertion electrodes. The reassembly of the original phase upon recharge does not necessarily involve the same kinetic pathways and intermediates as the production of the elemental metal and LiF during discharge. Thus, it may not be possible to remove the hysteresis entirely either by engineering of devices or by improving the material properties to ensure faster rate capability. This property

has an adverse effect on the round-trip efficiencies, and may make conversion electrodes unsuitable for Li-ion batteries unless a solution can be found to this problem.

Future Directions

Because none of the cathode materials discussed above are ideal for every application, the search for new insertion electrodes continues. Batteries are relatively simple devices, but the simultaneous requirements for high energy density, long cycle life, safety, and low cost impose stringent restrictions upon the choices available for cathode materials. The highly successful example of LiFePO_4 has directed researchers toward the exploration of other poly-anionic compounds that may share its excellent thermal stability at high states of charge. It is now evident that nanostructuring and/or conductive coatings can overcome kinetic and electronic limitations, allowing materials that would once have been thought of as unsuitable for electrodes to be considered. Changes in the phase behavior of nanoparticulate materials (in comparison to the conventionally sized powders) can render compounds electroactive that, in bulk form, appear to be unpromising due to their insulating nature. The shortened diffusion distances for lithium in nanoparticles may enable high rate capability in powders that appear to have severe rate limitations when micron-sized or larger. While this allows the menu of potential cathodes to be greatly expanded, the concept of “going nano” should be approached with caution. It is most successful when it is applied to materials that undergo redox well within the electrolyte stability range, such as with LiFePO_4 . The increased surface area of nanoparticulate powders compared to conventionally sized materials exacerbates any tendency toward irreversible reaction with electrolytes. In addition to the very serious safety concerns this raises, the paradoxical result may be to lower rate capability due to the increased presence of resistive reaction layers on cathode particle surfaces [262]! Nano-sizing may also adversely impact practical specific energies because processing into electrodes becomes more difficult. It is often necessary, for example, to add more carbon to the composite cathode to ensure good electrical connectivity, but this contributes dead weight. High surface area particles also do not

pack well, leading to decreases in the tap densities and lower energy densities. Ensuring that nanoparticles are regularly shaped rather than irregularly can ameliorate these tendencies, however [263]. Another potentially useful approach is to synthesize mesoporous materials [264] in which the particles are micron-sized but contain pores of controlled sizes and distributions so as to maximize contact between the electrolyte and active material. This effectively shortens diffusion distances, while minimizing the tap density effects and maintaining the ease of electrode processing.

The use of nano metric or very thin coatings on cathode particle surfaces to improve the electronic conductivity of a material, to decrease dissolution, suppress oxygen loss, or to extend the operating voltage range is somewhat less problematic than simply nano-sizing cathode powders. In principle, this may allow using a wider variety of materials, including high-voltage/high-energy electrodes safely, without compromising cycle life or requiring the use of exotic electrolytes. Here the challenge is to identify and prepare coatings that prevent contact with electrolyte, yet allow the transport of lithium ions. They must also remain essentially defect-free over many cycles in which the cathode particles may undergo significant volume changes. A related concept is the preparation of “core-shell” or compositionally graded materials in which two or more compounds are combined in the same particle [265]. The core of the material can be a high-capacity material and the outer shell one that has lower energy but better thermal stability, for example. A difficulty is the tendency for the shell to become detached from the core if the volume changes upon cycling are not carefully matched. A compositionally graded material is less subject to these stresses, but more complex to prepare.

Researchers continue to look for materials that can deliver higher capacities and energies than those currently available. The layered-layered composite materials (i.e., the solid solutions between Li_2MnO_3 and $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ or $\text{LiNi}_x\text{Co}_{1-2x}\text{Mn}_x\text{O}_2$), which are very high capacity once they are activated in electrochemical cells, are a recent promising development. Cathodes that can undergo more than one oxidation state change per metal center reversibly could substantially increase the capacity of lithium-ion batteries. These include the Li_2MSiO_4 compounds and

conversion electrodes discussed above, but these require much more work before they can be envisioned for use in lithium-ion batteries.

The challenges presented by these new materials illustrate the delicate balance of performance characteristics, cost, and safety that the battery electrode designer must be able to meet. There is now renewed interest among researchers in lithium metal batteries, because of the very high energy densities that might be achieved. However, now instead of intercalation electrodes, developers are reconsidering the use of sulfur and air (oxygen) cathodes for lithium metal batteries intended for vehicles. The extremely high theoretical capacities of these materials (e.g., over 1,600 mAh/g for sulfur) in lithium batteries are certainly tantalizing, but the difficulties associated with their use have proven daunting. In the case of sulfur, LiS_x intermediates dissolve in the electrolyte solutions, eventually migrating to the lithium anode and precipitating as Li_2S . The development of the protected lithium electrode (PLE) by PolyPlus Battery Company (Berkeley, CA) has extended the cycle life significantly, and Li/S batteries are now used for some military applications. In PLEs, the lithium anode is covered by a thin dense protective film (e.g., a lithium-ion conducting ceramic such as Lisicon, a ceramic with the Nasicon structure), which not only prevents contact with soluble intermediates but also with the electrolyte. An interlayer between the lithium and the protective layer is also needed to prevent reduction of the latter. Thus, in principle, it is possible to operate lithium cells with a wide variety of electrolytes, including aqueous ones. A lithium/water battery has even been developed for niche applications, although it is intended for use only as a primary, at present.

While in principle it should be possible to operate a lithium/air battery using a PLE to prevent contact of lithium with adventitious water and CO_2 in the atmosphere, rechargeable systems have so far eluded success. The reduction of oxygen itself is somewhat sluggish, necessitating the use of a catalyst. The Li_2O_2 , which is the reaction product when nonaqueous electrolytes are used, precipitates out during discharge and eventually clogs the pores of the air electrode structure. While some researchers have claimed to have successfully recharged a lithium/air battery, the large hysteresis observed suggests that a side-reaction involving the

electrolyte is responsible for the charging behavior instead of reoxidation of Li_2O_2 to oxygen.

Ultimately, the success or failure of lithium/sulfur or air systems, however, hinges upon convincing demonstration of safe and reliable operation of the lithium anode over the many cycles required for applications requiring rechargeable devices.

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Battery Components, Active Materials for

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Glossary

Battery efficiency Output energy/input energy for storage of electrical energy as chemical energy.

Electrolyte window Separation of electrolyte LUMO and HOMO energies of a liquid electrolyte and of conduction and valence bands of a solid electrolyte.

Fermi energy Electrochemical potential of a solid.

HOMO Highest occupied molecular orbital.

Insertion compound A host solid into which a working ion (guest) can be inserted/extracted reversibly over a solid-solution range.

LUMO Lowest unoccupied molecular orbital.

Polarization, $\eta = V_{OC} - V(q, I)$ Loss of battery voltage at a state of charge q due to resistance to ion transfer inside battery cell where an electronic current I is flowing outside of battery.

Rate of charge/discharge, nC Time, $(60/n)$ min, for complete discharge or charge of a battery or cell; it is also a measure of the current.

Redox couple Cation $M^{(m+1)}/M^{m+}$ mixed-valent energy applicable to localized-electron configurations.

SEI layer Solid/electrolyte interface (passivation) layer at an electrode having its Fermi energy outside the electrolyte window.

Separator A solid layer permeable to the working ion that separates anode from cathode to prevent electron transfer between them inside a battery cell.

Spin state Refers to spin of a redox couple, which may be reduced (low-spin state) from its free-ion value (high-spin state) by a ligand-field splitting of energies of atomic orbitals that is larger than the Hund intraatomic-exchange splitting of electron spins.

State of charge Amount of chemical energy in a battery or cell relative to the total energy available.

Tap density A measure of the volume density, which increases with compaction of the active electrode particles.

Working ion Ion carrying ionic current inside a battery cell.

Definition

The active materials of a battery are the chemically active components of the two electrodes of a cell and the electrolyte between them.

A battery consists of one or more electrochemical cells that convert into electrical energy the chemical energy stored in two separated electrodes, the anode and the cathode. Inside a cell, the two electrodes are kept apart by an inert separator that is permeable to a liquid electrolyte or by a solid electrolyte. The electrolyte allows transfer from the anode to the cathode of only the working cation, which carries the positive charge associated with the chemical reaction between the electrodes; the electrolyte and separator force the electrons of the reaction to flow outside the battery where they can be stopped (open circuit) or discharged from the anode to the cathode through a load where

they do work. In a rechargeable battery, the chemical energy can be restored by the application of a reverse charging current. The active materials determine such parameters as the electric-power capability of a battery, its energy density, its calendar and cycle life, its cost, and its safety. Each battery application has a different set of requirements. Tailoring of the active materials to the demands of a particular application is an ongoing process. These applications range from the powering of heart pacemakers to portable electronic devices to electric vehicles to electrical-energy storage for the grid. The active materials used in batteries for some of these different applications are discussed.

Introduction

The conversion of chemical energy to electricity was first demonstrated in 1800 by Volta, who constructed a battery – the *voltaic pile* – from alternating plates of silver and zinc separated by a cloth soaked in a salt solution. In 1806, Davy used the electricity from a voltaic pile to convert electrical energy into chemical energy by separating electrochemically alkali metals from their hydroxides. The electrochemical cell was invented in 1836 by Daniell, who immersed Zn in an aqueous $ZnSO_4$ solution and copper in a $CuSO_4$ solution in separate tubes; the two tubes were joined by a salt bridge containing a porous glass frit. This cell was called a *galvanic cell* in memory of Galvani, who had discovered in the 1790s that two different metals and a salt solution could cause muscle contractions in a frog's leg. Galvanic cells were developed to supply electricity before electric generators were available. The gifted experimentalist, Michael Faraday, began his career as an apprentice in Davy's laboratory; he later went on to lay the foundations for the science of electrochemistry and the development of the modern battery. It was Faraday who was to refer to the two different metals of a voltaic pile and of a galvanic cell as electrodes; the reductant was called the anode and the oxidant the cathode. The salt solution connecting the two electrodes by an ionic current was the electrolyte. Negatively charged ions are referred to as anions and positively charged ions are referred to as cations because they are attracted, respectively, to the anode and the cathode when electrons flow from the anode to the cathode.

Batteries

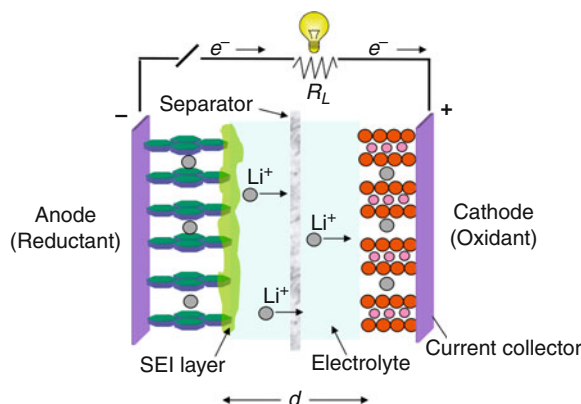
A *battery* consists of one or more electrically connected *electrochemical cells* that store chemical energy in their two *electrodes*, the *anode* and the *cathode*; the battery converts the chemical energy into electrical energy on *discharge*. The electric output of a battery is a *discharge current* I at a voltage V to give an electric-power output $P = IV$. The power capability is expressed as *specific* or *gravimetric power* in watts per kilogram (W/kg) or *volumetric power density* in watts per liter (W/L). The *energy density* of a battery is the amount of *electrical energy* QV that is available from a fully charged battery per unit weight or volume; it is expressed as *specific* or *gravimetric energy* in watt-hours per kilogram (Wh/kg) or as *volumetric energy density* in watt-hours per liter (Wh/L). Q is the total charge transported by I over the time Δt of a complete discharge

$$Q = \int_0^{\Delta t} I dt = \int_0^Q (dq/dt) dt \quad (1)$$

and Q/weight (Ah/kg or mAh/g) is the *capacity* of the battery. The voltage of a battery can be increased by connecting individual electrochemical cells in series; the current per cell for a given battery current can be decreased and therefore the time for a full discharge can be increased by connecting cells in parallel. The larger the voltage and capacity of an individual cell, the fewer the cells in the battery.

A *primary battery* is discarded after providing electrical power until its chemical energy is exhausted. A *secondary battery*, also called a *rechargeable battery* or an *accumulator*, can have its spent chemical energy restored by the application of a *charging current* in a direction opposite to that of the discharge current. The *cycle life* of a secondary battery is the number of discharge/charge cycles it can support before losing 20% of its capacity. The energy loss per cycle is the difference between the electric energy used to charge the battery and that gained on discharge; the electrical energy gained on discharge divided by the electrical energy spent on charge is the *efficiency* of a secondary battery for storage of electrical energy.

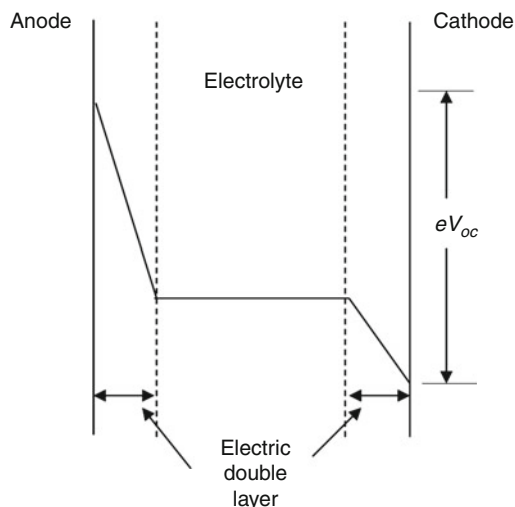
Figure 1 illustrates schematically the components of an individual electrochemical cell. The *anode* is a reductant and the *cathode* is an *oxidant*. Inside the



Battery Components, Active Materials for. Figure 1 Schematic showing components of $\text{LiC}_6/\text{Li}_{1-x}\text{CoO}_2$ cell. Internal Li^+ -ion and external electronic (e^-) currents I_i and I are shown for discharge with switch closed. The SEI passivation layer is formed because the energy E_{FA} of the LiC_6 anode is higher than the LUMO of the carbonate electrolyte (see Fig. 3)

cell, the two electrodes are kept apart by a physical barrier, a *separator*, that prevents any electron transfer between them inside the cell. However, the two electrodes are connected electrically inside the cell by an *electrolyte* that conducts a *working ion* and is an electronic insulator. A liquid electrolyte permeates a chemically inactive, porous separator; a solid electrolyte also acts as a separator. The working ion is normally a cation: H^+ , Li^+ , or Na^+ . Chemical reaction between the two electrodes of a cell involves both electron and working-ion transfer between the electrodes. The electrolyte forces the electrons to flow outside the cell while allowing the working ion to be transported inside the cell. Therefore, a battery has a *negative terminal* that collects electrons via a *current collector* from all the cell anodes for delivery to an external circuit and a *positive terminal* that receives electrons from the external circuit and delivers them via a current collector to all the cell cathodes during a battery discharge.

External connection of the battery terminals allows an electronic discharge current I to pass through an external load of resistance R_L , where it does work, to the cathode where it neutralizes the ionic current I_i inside the battery. Thus, on discharge the battery transforms its chemical energy into electrical energy at the load. The much higher electronic conductivity σ_e compared to the working-ion conductivity σ_i means that a cell is



Battery Components, Active Materials for. Figure 2 Voltage levels in the various sections of a cell at open circuit. The double layers at the anode and the cathode have different structures and compositions

fabricated with a small thickness/area ratio. Disconnection of the two battery terminals stops not only the external discharge current, but also the internal ionic current since, without charge neutralization, an internal electric field between the cell electrodes is built up to stop further flow of the working ion. This electric field is expressed as a voltage between the terminals of a cell at open circuit, the *open-circuit voltage* V_{oc} , with a positive charge at the cathodic positive terminal and a negative charge at the anodic negative terminal. Mobile ions in the electrolyte form *electrical double layers* at the surfaces of the electrodes to neutralize the electrode charge, and the voltage drop inside the cell is across the double layers, Fig. 2.

This entry describes strategies used by the chemists to identify appropriate active materials, electrodes and electrolyte, for the individual electrochemical cells of a battery.

Fundamental Constraints

Maintaining Electrode–Electrolyte Contact

Ion transfer across the electrode/electrolyte interfaces requires retention of a good electrode–electrolyte contact during discharge and charge. Since ion and electron transfers between the electrodes change the volumes of the electrodes, it is advantageous to have

a liquid or polymer electrolyte contacting solid crystalline electrodes; a solid electrolyte is needed to keep the electrodes apart if one or both of the electrodes is a liquid or a gas.

Electrolyte Window

The *window* of a liquid electrolyte is the energy gap E_g between its lowest unoccupied molecular orbital (LUMO) and its highest occupied molecular orbital (HOMO). The window of a solid electrolyte is the energy gap E_g between the bottom of the empty electronic conduction band, E_c , and the top of the filled electronic valence band, E_v . Figure 3 illustrates how the window of an electrolyte constrains the V_{oc} of a cell.

Figure 3a shows the case of solid electrodes having anode and cathode Fermi energies E_{FA} and E_{FC} in their electronically conductive state. An E_{FA} or E_{FC} may lie in a partially filled conduction band or in a mixed-valent redox couple. An E_{FA} above the electrolyte LUMO will reduce the electrolyte and an E_{FC} below the electrolyte HOMO will oxidize the electrolyte. Therefore, thermodynamic stability restricts the open-circuit voltage to

$$eV_{oc} = E_{FA} - E_{FC} \leq E_g \quad (2)$$

where e is the magnitude of the charge of an electron. However, charge transfer at an electrode/electrolyte interface may create a double layer and/or a passivation layer that blocks a subsequent ionic transfer at open circuit to stop any further electrolyte reduction or oxidation and therefore to give a *kinetic stability* for a limited $(eV_{oc} - E_g) > 0$. A passivation layer is referred to as a *solid-electrolyte interphase* (SEI); it should not block ion or electron transfer under closed-circuit conditions.

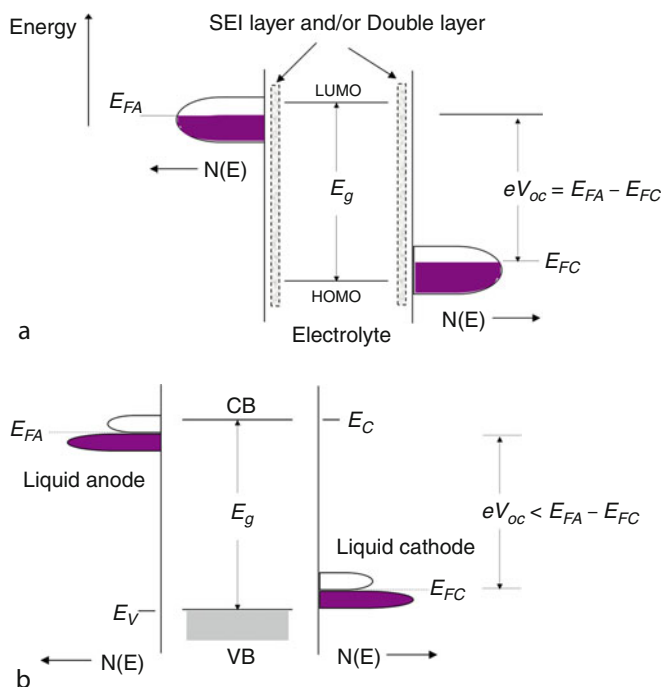
Solid electrolytes, Fig. 3b, are chosen to have a window $E_g > eV_{oc}$.

Ionic Conductivity

Kinetic limitations on the rate of working-ion transfer between electrodes cause the cell voltage V to drop relative to V_{oc} . The voltage drop

$$\eta(q, I) = V_{oc} - V \quad (3)$$

is called the *polarization* or the *overvoltage*; q is the state of charge. The polarization is due to the resistance to ionic motion inside the cell.



Battery Components, Active Materials for. Figure 3

Definition of the electrolyte window E_g for (a) liquid and (b) solid electrolytes. The E_{FA} and/or E_{FC} of solid electrolytes may lie in either a band of one-electron states as in (a) or a multielectron redox couple as in (b); for liquid electrodes, they lie in a mixed-valence redox couple

Ions move diffusively. Therefore, the ionic conductivity is given by

$$\sigma_i = (nq^2/kT)D_i \sim Nc(1-c)\exp(-\Delta H_m/kT) \quad (4)$$

where $n = cN$ is the density of carriers of charge q ; $D_i = D_0 \exp(-\Delta G_m/kT)$ is the ionic diffusion coefficient containing a Gibbs free energy $\Delta G_m = \Delta H_m - T\Delta S_m$ for an ion to move from one position to another. The motional enthalpy ΔH_m is an activation energy for ion motion, and $(1-c)$ is the fraction of sites that are empty into which ions can move.

In a strong acidic or alkaline aqueous electrolyte, $n = cN$ is large and ΔH_m is small so long as the water molecules are free to rotate as in a liquid; the H^+ ions hop within hydrogen bonds, but molecular rotation is needed to subsequently reorient the hydrogen to a new bond direction (Grotthus motion). In a liquid aqueous electrolyte, the H^+ -ion conductivities are generally $\sigma_H \approx 1$ S/cm at 20°C. However, the window of an aqueous electrolyte is only 1.23 eV, which has led to consideration of nonaqueous electrolytes. Since H^+

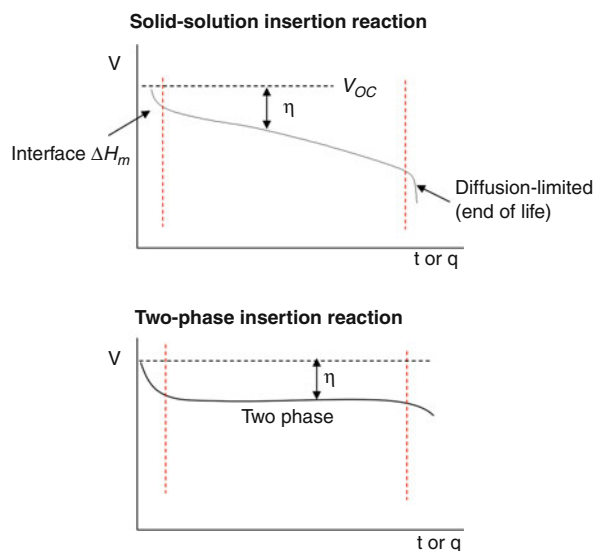
ions are not mobile in nonaqueous liquid electrolytes, the Li^+ ion is normally used in these electrolytes. Few organic solvents dissolve a sufficient concentration of lithium salts with good separation of the Li^+ ions from the anion of the salt. The Li^+ -ion conductivities in the best nonaqueous liquid electrolytes are $10^{-3} < \sigma_{Li} < 10^{-2}$ S/cm at 20°C.

Solid cathodes of secondary-battery cells are *insertion compounds*. An insertion compound has a *host* crystalline structure into which a *guest* working ion can be inserted/extracted reversibly into/from its interstitial space while the ionic charge is being neutralized by reduction/oxidation of the host structure with electrons coming from/sent to the external circuit. These electrodes are mixed ionic/electronic conductors. During an insertion or extraction reaction, the essential architecture of the host structure remains intact throughout the process, but two types of insertion reaction need to be distinguished: (1) a single-phase solid-solution reaction between the guest and the host; (2) a two-phase reaction. A first-order transition

between two phases results in the coexistence of the two phases; a first-order transition may not be reversible, but where the host undergoes an ion-displacement transition that separates a phase rich in the working ion from one that is poor in the working ion, the two-phase reaction can be reversible. In a single-phase solid-solution reaction, the output voltage V of the cell decreases monotonically with its state of charge as is illustrated schematically in Fig. 4a. The *state of charge* of a cell refers to the fraction of the full-charge chemical energy existing in a partially charged cell. Where the host structure undergoes a first-order structural change during discharge, the output voltage V of the cell is independent of the state of charge over the two-phase region as is illustrated in Fig. 4b. This behavior follows from the Gibbs phase rule, which states that the number of thermodynamic parameters that are free to vary is

$$F = C - P + 2 \quad (5)$$

where P is the number of coexisting phases and C is the number of components, guest and host, taking part in the reaction. Where two phases coexist, $C = P$ and $F = 2$. Since temperature and pressure are specified, there is



Battery Components, Active Materials for. Figure 4 Schematic profiles for (a) a solid-solution insertion reaction and (b) a two-phase insertion reaction showing the polarization $\eta = V_{OC} - V$. Note: Two-phase reactions retain the higher voltage found at the onset of the two-phase region

no degree of freedom left, so other parameters such as voltage have to be constants. In an insertion reaction, the host interstitial space into which the working ion can be inserted may be 1D, 2D, or 3D (D = dimensional) depending on the host structure.

In Fig. 4a, three ion-transfer processes are distinguishable: (1) an *activation polarization* due to the energy ΔH_m required to transfer ions across the electrode/electrolyte interfaces, (2) a change in $E_{FA} - E_{FC}$ and (3) an end-of-life *concentration polarization*. The slope in region (2) of a similar $V(q)$ vs. I curve gives the *ohmic polarization*. The activation polarization is manifest on the initiation of discharge; the ohmic polarization is manifest by the slope of the $V(I)$ profile in mid-discharge. At the end of life, either the concentration of working ions reaching the cathode is depleted and/or the concentration $(1-c)N$ of the cathode acceptor sites at the electrolyte/electrode interface is depleted to where the ionic diffusion current is no longer able to keep up with a fixed discharge current I . The increase in η causes a decrease in V at the end of life, and this decrease occurs at a larger state of charge the higher is I and, from Eq. 4, the lower is the temperature T . The end-of-life drop-off in V is also referred to as the *diffusion-limited* regime of the $V(t)$ profile. The loss of capacity at higher I and lower T is *reversible*; capacity is restored at lower discharge currents I and higher temperatures T where the working-ion profile across the electrolyte/electrode interface approaches more closely the equilibrium profile. Thus, the reversible Q of Eq. (1) decreases with increasing I ; $Q = Q(I)$. Clearly, a fast diffusion of the working ion not only in the electrolyte, but also in any insertion-compound electrode is needed for a secondary power battery.

Energy Density

The specific energy QV/weight of a cell depends not only on the voltage V of the cell, but also on the total charge Q per kilogram that is transported between the electrodes. In order to achieve a high cell voltage, the E_{FA} of the anode and the E_{FC} of the cathode need to be matched to the LUMO and the HOMO, respectively, of an electrolyte with a large window E_g between its LUMO and HOMO. In a secondary battery, Q is the total charge that is transported reversibly between the electrodes. In a secondary battery in which the cells

are assembled in the discharged state, Q is limited to the number and charge of working ions that can be extracted reversibly from the cathode host. However, where the anode develops a non-blocking SEI layer, Li^+ ions are trapped irreversibly in the SEI layer during the initial charge, which reduces the capacity available from the cathode on subsequent charge/discharge cycles. To eliminate this loss of cathode capacity, it would be necessary to form the SEI layer on the anode before assembling the cells of a battery.

In addition to formation of an SEI layer on the anode, chemical reactions between the cathode and the electrolyte or within the cathode can deplete the amount of active cathode material. These reactions introduce an *irreversible* capacity loss that is expressed as a *capacity fading* with the number of charge/discharge cycles. The *cycle life* of a cell is the number of discharge/charge cycles a cell can undergo without too great an irreversible capacity loss to be useful; the *service life* of a cell is the length of time over which the cell retains more than 80% of its capacity. The service life depends on the cycle life, that is, the cell use as well as on the age of the cell.

Morphology

In order to minimize the reversible capacity loss at higher discharge/charge currents, solid electrodes are made porous so as to maximize the electrode/electrolyte interface area per unit planar area of the electrode. Solid porous electrodes are commonly a complex composite of the active material in the form of small particles coexisting with and contacting a current-passing additive such as carbon, metal particles, or a conductive polymer; the conductive additive percolates through the composite mass to connect electronically the active particles to one another and to the electrode current collector. This composite mass is commonly held together by a chemically inactive binder such as Teflon. Typically, such a composite electrode has about 30% porosity percolating through it so as to allow impregnation of the pores by a liquid electrolyte in order to have the electrolyte contact every active particle. The resulting electrode/electrolyte interface area is complex, and the ionic currents within the composite electrode are tortuous. Modeling the current flows within an electrode as well as the composite

morphology has become an important tool in the design of a composite electrode and of the distribution of primary currents in the metallic current collectors.

Heat

The net useful energy released for a given chemical reaction between the electrodes is the enthalpy ΔH of the Gibbs free energy

$$\Delta G = \Delta H - T\Delta S \quad (6)$$

where $T\Delta S$ is the heat associated with the entropy change ΔS of the reaction at an absolute temperature T . For a fixed T , this heat is reversible, that is, it is exothermic on discharge and endothermic on charge or *vice versa*. In electrical terms,

$$\Delta S = nFdV/dT \quad (7)$$

where n is the number of electrons per mole of reactants participating in the discharge reaction and F is the Faraday constant, that is, the amount of charge transferred when one equivalent weight of mass reacts. From Eqs. 6 and 7, the reversible heat on discharge is $nFT(dV/dT)$, which may be positive or negative, exothermic or endothermic. In addition, the internal resistance R_b of a cell creates heat I^2R_b that must be dissipated. *Thermal runaway* occurs if the internal heat causes an electrode reaction with the electrolyte to become self-sustaining, the reaction entering an autocatalytic mode. This situation is responsible for fires associated with battery operations, and an internal electronic short circuit between the electrodes occasioned by dendrite growth from an anode across the electrolyte to the cathode with repeated cycling can trigger such an event where the electrolyte is flammable.

Cost

Cost as well as safety, capacity, and power capability are constraints on any commercial device. Lower cost requires not only low-cost, nontoxic materials, and simple battery-stack management, but also a long service life, ease of manufacture, and a minimization of the number of cells to achieve a specified voltage and discharge time. Safety of a secondary battery at an acceptable cost favors either a nonflammable electrolyte or a solid-electrolyte separator that blocks

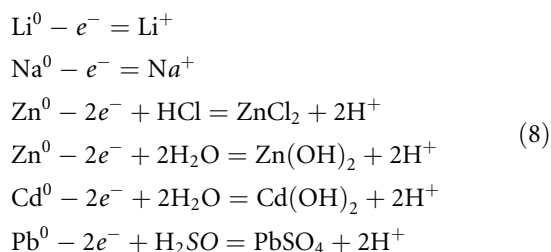
short-circuiting from any dendrite formation on a solid anode where dendrite formation threatens short-circuiting of cells on repeated cycling. A long service life requires elimination of irreversible chemical reactions within the individual cells.

The cost and service life of secondary batteries for electric vehicles must compete against the cost and service life of the internal combustion engine. In their favor is elimination of the cost to the environment of distributed emissions of the greenhouse gas CO₂; and if charging of the battery of the electric vehicle can be done with wind or radiant solar energy, all CO₂ emissions associated with the vehicle can be eliminated.

Electrode Reactions

Primary batteries [1] having liquid electrolytes generally use a solution or a solution-precipitation reaction of an element at the anode and a displacement or insertion reaction at the cathode. Most secondary batteries use insertion reactions at a solid cathode and may also use insertion reactions at the anode.

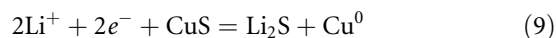
Some common elemental solution or solution-precipitation reactions are:



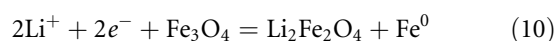
The E_{FA} of Li⁰ lies above the LUMO of a nonaqueous liquid-carbonate electrolyte containing a lithium salt. Although a non-blocking SEI passivation layer is created at the surface, lithium is not plated back uniformly during a charge; it forms a rough, mossy surface that, on repeated discharge/charge cycles, develops dendrites that can grow across the electrolyte to contact the cathode. Therefore, with a liquid electrolyte Li⁰ is only used as an anode in a primary battery or in half-cells used to test the performance of candidate cathode materials for secondary batteries. However, it may be used in a secondary cell having a solid Li⁺-ion electrolyte that blocks dendrite growth across it and is not reduced on contact with a dendrite.

The E_{FA} of Zn⁰ lies 0.76 eV above the 2H⁺/H₂ LUMO of an aqueous electrolyte, which has previously prohibited its use in a secondary battery. However, it is used successfully as the anode of a primary cell having either an HCl acidic or KOH alkaline electrolyte. The Cd²⁺/Cd⁰ couple at 0.40 eV above the 2H⁺/H₂ couple is better matched to the aqueous LUMO, so Cd has been the preferred anode for a secondary alkaline battery with a KOH electrolyte. A lower electrochemical potential of an alkaline versus an acidic electrolyte allows the double layer in an alkaline electrolyte to lower the E_{FA} of Cd to below the 2H⁺/H₂O LUMO. The Pb²⁺/Pb⁰ couple is only 0.13 eV above 2H⁺/H₂, so it provides a reversible anode reaction in a sulfuric-acid electrolyte. In all cases with aqueous electrolytes, the anode-electrolyte reaction releases mobile working H⁺ ions to react with the cathode.

In a displacement reaction, the working ion displaces a cation of the electrode as is illustrated by the cathodic discharge reaction

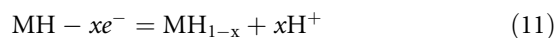


Normally, such a first-order reaction is not easily reversed, and to date cathodes undergoing such a reaction are only found in primary batteries. However, they represent a Q corresponding to two electrons per electrode cation to give a large capacity. Although displacement reactions that leave a host framework intact may be reversible, for example,



the associated volume changes have made these reactions impractical unless they are buffered by an amorphous carbon matrix.

In a reversible insertion reaction, the working ion is inserted as a guest into a host structure forming either a solid solution in a single-phase reaction or two phases in a first-order reaction in which ionic displacements of the host segregate the electrode into guest-rich and guest-poor phases. For example, two anode reactions are the single-phase reaction of a metal hydride MH



and the lithiated graphite two-phase reaction



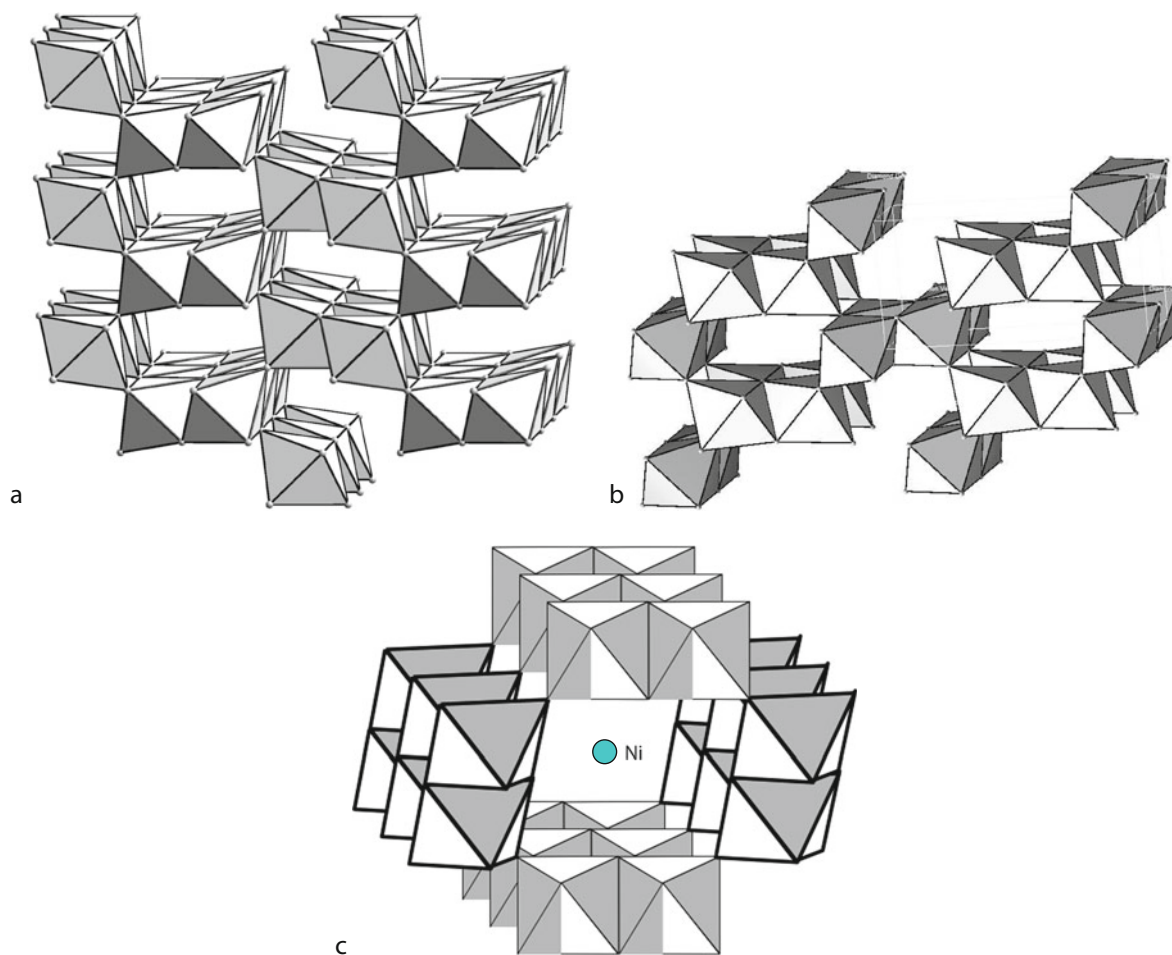
in which graphene sheets are shifted in stages relative to one another on Li insertion (Fig. 9). In anodes, the guest is inserted on charge and extracted on discharge. As a cathode, the guest is inserted on discharge and extracted on charge.

Primary Batteries

Zinc–Manganese Batteries

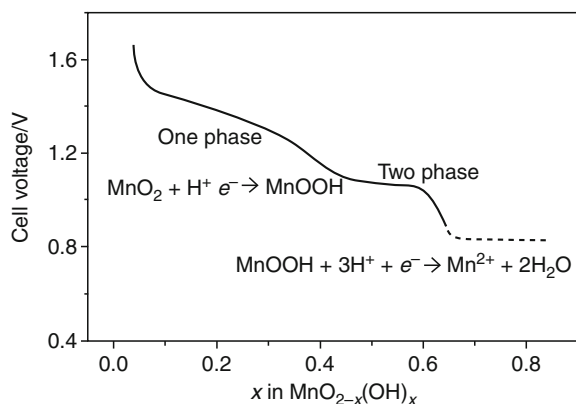
Zinc–manganese batteries [1] dominate the primary-battery market. These batteries are of two types depending on the pH of their aqueous electrolyte. Each uses a carbon-MnO₂ cathode; the carbon provides electronic conductivity. The MnO₂ is best

prepared as αMnO₂ or γMnO₂, which have structures, Fig. 5, with 1D channels into which H⁺ ions can be inserted. The Leclanché cell, Zn/HCl/MnO₂, is acidic, and the Zn anode undergoes a Zn-solution reaction; Zn²⁺ ions enter a ZnCl₂ + NH₄Cl salt solution to displace 2H⁺ ions to the cathode. In the alkaline cell, Zn/KOH/MnO₂, the Zn anode reacts with the aqueous electrolyte to form Zn(OH)₂ + 2H⁺; the Zn(OH)₂ subsequently transforms to ZnO↓ + H₂O. As shown in Fig. 6, the discharge voltage of a zinc–manganese battery exhibits two ranges, one corresponding to a single-phase solid-solution reaction



Battery Components, Active Materials for. Figure 5

Structures of (a) α – MnO₂, (b) γ – MnO₂, (c) Ni-exchanged cryptomelane. Octahedral sites of MnO₂ share edges along the c-axis. H⁺ ions are inserted into the 1 × 2 tunnels

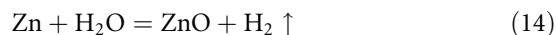


Battery Components, Active Materials for. Figure 6 Discharge voltage profile of the $\text{MnO}_{2-x}(\text{OH})_x$ cathode of a Zn/ MnO_2 primary battery showing solid-solution (one-phase) and two-phase compositional ranges

and the other to a two-phase reaction that is irreversible. An octahedral-site Mn(III) ion has a twofold orbital degeneracy, and at a sufficient concentration of Mn(III) ions, a cooperative site distortion to remove the degeneracy introduces a first-order displacive transition of the host structure. The Mn(III)-rich phase at the surface undergoes a disproportionation reaction: $2 \text{Mn(III)} = \text{Mn(II)} + \text{Mn(IV)}$ that is followed by an *irreversible* dissolution of Mn(II) into the electrolyte. The better match of the E_{FA} of Zn^0 to the $2\text{H}^+/\text{H}_2\text{O}$ LUMO of the KOH electrolyte makes the alkaline cell more reliable and gives it a better performance at higher discharge rates. However, in the discharge reaction, a mole of H_2O per two moles of MnO_2 is consumed, which increases the impedance of the cell where the amount of electrolyte has been minimized to maximize the cell capacity. Ni-exchanged cryptomelane, Fig. 5c, alleviates this problem.

With 1D tunnels in the MnO_2 cathode, it is critical to remove impurities and structural stacking faults that would block a tunnel. Moreover, since the $\text{Zn}^0/\text{Zn}^{2+}$ couple lies above the $2\text{H}^+/\text{H}_2$ LUMO of the electrolyte, the Zn anode of the alkaline cell consists of Zn particles of selected size bound with the KOH electrolyte in a stabilizing gelling agent to suppress H_2 evolution. The selection of the gelling agent and the size of the Zn particles are critical. The gelling agent creates

a passivating SEI layer on the Zn to inhibit it from reducing the water at open circuit:

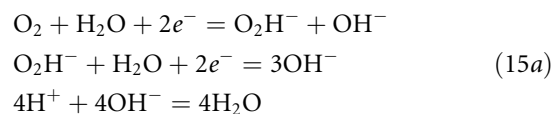


Zinc–Air and Silver–Zinc Batteries

The alkaline zinc–air battery has the highest energy density of all aqueous batteries since only the Zn-powder anode is contained in the cell; the other reactant, oxygen, is available from the surrounding air. The capacity of a cell is dictated by the amount of fine Zn powder that is available for discharge. Nevertheless, a light cathode structure is present; it consists of a porous carbon or nickel mesh containing both the liquid electrolyte to convey H^+ ions and MnO_2 or other particles as catalyst in the pores. Gaseous O_2 is given access to the porous carbon where it penetrates the pores to be reduced on the MnO_2 at a triple-phase boundary (TPB) by the reaction

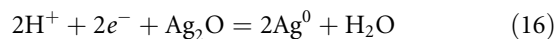


However, the oxygen–reduction reaction Eq. 15 forms an intermediate peroxide:



and breakdown of the peroxide H_2O_2 and/or its radical O_2H^- is rate-limiting. These cells are available in sizes small enough to fit into the ear to power a hearing aid.

The silver–zinc battery also uses a KOH alkaline electrolyte. In this battery, the cathode undergoes the displacement reaction



This battery is primarily used in button cells for small portable devices such as watches.

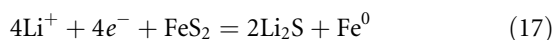
Lithium Primary Batteries

Primary lithium cells use a lithium-metal anode and a nonaqueous electrolyte having a larger window than the 1.23 eV of an aqueous electrolyte. Both liquid and solid Li^+ -ion electrolytes can be used.

Liquid Electrolytes. The carbonates dissolve a fair concentration of lithium salts, normally LiClO_4 or LiSO_3CF_3 in propylene carbonate-dimethyl ether in

primary cells. Since the Li^0/Li^+ couple lies about 1 eV above the LUMO of the carbonate, dimethyl ether is added to react with the Li^0 to form a passivating SEI layer. With a passivating layer on the Lithium anode and an electrolyte window $E_g \approx 3.5$ eV, cell voltages of 4.0 V or higher are possible. With a higher voltage V , the lithium primary batteries provide a larger energy density, but Li^+ -ion transport across the SEI layer and a σ_{Li} in the nonaqueous electrolyte significantly lower than the σ_{H} in a strong acidic or alkaline aqueous electrolyte reduces the rate capability of a Lithium primary battery at 20°C. The solid-cathode insertion compounds CF_x and MnO_2 are thermodynamically stable and provide a long shelf life; Li/CF_x and Li/MnO_2 batteries have a $V = 3.0$ V and are designed for relatively low-rate applications.

The FeS_2 cathode of a Li/FeS_2 battery undergoes a two-step displacement reaction



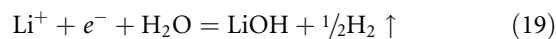
in which an amorphous Li_2FeS_2 is first formed by the breaking of the disulfide $(\text{S}_2)^{2-}$ ions of FeS_2 . This battery only provides $V = 1.6$ V in the first step, but at higher temperatures it gives a high-rate performance superior to that of the alkaline Zn/MnO_2 cells.

The Li/I_2 cell is used preferably for implanted heart pacemakers; the di-iodine bond is broken at $V = 2.7$ V in the cathode reaction



Solid Electrolytes. A *protected Lithium anode* is under development for both primary and secondary batteries that promise much larger capacities. This strategy is illustrated by the $\text{Li}/\text{seawater}$ primary battery in which a Lithium anode is immersed in a nonaqueous electrolyte, the *anolyte*, that is separated from seawater contacting a cathode current collector by a Li^+ -ion solid-electrolyte separator. The seawater acts as a liquid cathode. Except for contact with a negative post, the Lithium anode and its anolyte are sealed in a compartment containing a Li^+ -ion solid-electrolyte wall that interfaces the seawater. The anolyte is chemically stable to both the Lithium and the solid electrolyte; the solid electrolyte must not be reduced on contact with the Li^0 anode. Moreover, either the seal or the compartment must be compliant to allow for the

change in volume of the Lithium on discharge. The seawater is not contained in an *open cell*; it is contained within a battery in a *closed cell*. The Li^+ ions from the anode react with water at the cathode current collector:

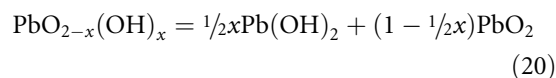


to give a constant voltage $V = 2.7$ V. The efficiency of a $\text{Li}/\text{seawater}$ secondary cell is not good, but other liquid cathodes, for example, $\text{Fe}(\text{CN})_6^{3-}/\text{Fe}(\text{CN})_6^{4-}$ in water, offer a more efficient electrical-energy storage than the seawater cathode and, with a solid electrolyte, permit a flow through of only the liquid cathode (see last section for flow-through rechargeable batteries).

Secondary Batteries with Aqueous Electrolytes

The *lead-acid battery* $\text{Pb}/\text{H}_2\text{SO}_4/\text{PbO}_2$ [1] provides a fast cell discharge at 2.0 V, it is relatively low-cost, and 98% of the batteries used in the USA are recycled. This battery has dominated the market for rechargeable batteries, but Pb is heavy and the practical energy density of the battery is only about 25% of its limited theoretical energy density (Wh/kg). Therefore, other secondary batteries are used for handheld devices and contend for the electric-vehicle market.

The Pb anode is matched to the $2\text{H}^+/\text{H}_2\text{O}$ LUMO of the aqueous H_2SO_4 electrolyte; during discharge, the Pb^{2+} ion forms PbSO_4 on entering the electrolyte to displace 2H^+ to the PbO_2 cathode. On reduction of the PbO_2 by electrons from the anode, H^+ ions are inserted into the PbO_2 to form $\text{PbO}_{2-x}(\text{OH})_x$. A kinetic stability impedes reaction of the reduced PbO_2 with the electrolyte, but electrons introduced into the Pb-6s band disproportionate into electron-rich $\text{Pb}(\text{OH})_2$ regions within the PbO_2 matrix



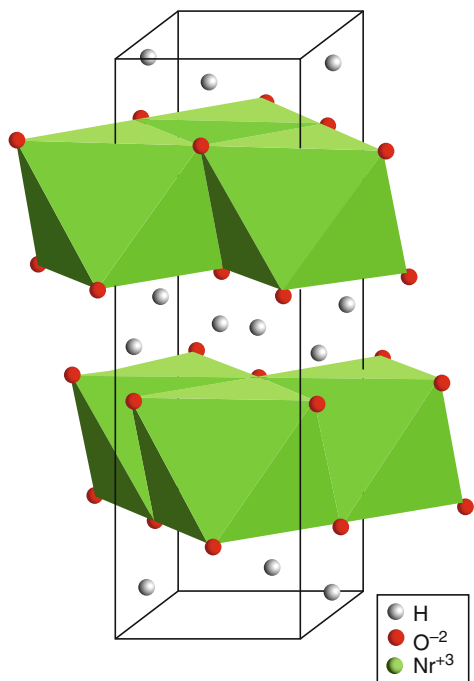
followed by a slow reaction



At open circuit, electrode reactions that charge the electrodes lead to a slow oxidation of the electrolyte with H_2 evolution at the anode and O_2 evolution at the cathode. These reactions represent an irreversible *self-discharge*. Once the electrolyte is introduced, the battery has a poor shelf life. Under development

are acidic aqueous electrolytes in which Pb(II) is soluble rather than condensing into the solid PbSO_4 . This development of the lead–acid cell promises a flow battery not requiring a separation membrane. The separation membrane of redox-flow batteries (see last section) remains a challenging problem for the aqueous redox-flow technology.

The *cadmium–nickel* cell, $\text{Cd}/\text{KOH}/\text{NiOOH}$, has its Cd anode and $\text{NiO}_{1-x}(\text{OH})_{1+x}$, $0 \leq x \leq 1$, cathode well-matched to the LUMO and the HOMO of the alkaline KOH electrolyte; the small, sealed cell gives a fast discharge and charge at a discharge voltage of 1.2 V. Like the Pb anode of the lead–acid battery, the Cd anode undergoes a solution-precipitation reaction in which Cd^{2+} reacts with the water of the electrolyte, Eq. 4, to form reversibly solid $\text{Cd}(\text{OH})_2$ and displace 2H^+ ions to the cathode. The cathode is the layered, monoclinic β -NiOOH of Fig. 7; it converts to hexagonal β -Ni(OH) $_2$ in a two-phase reaction on insertion of H^+ to give a plateau in the $V(x)$ discharge curve at 1.2 V versus $\text{Cd}/\text{Cd}(\text{OH})_2$. In β -NiOOH, the oxygen stacking along the c -axis within a unit cell is ABCA, Fig. 7;



Battery Components, Active Materials for. Figure 7 Layered structure of monoclinic β – NiOOH

the H^+ ions are located preferentially in the trigonal-prismatic sites between A-A stackings. Overcharging introduces water into the H-depleted galleries to give γ -NiOOH· $\gamma\text{H}_2\text{O}$. Best performance of the β -NiOOH- β -Ni(OH) $_2$ cathode is found with small particles having a large defect content. The gelatinous $\text{Cd}(\text{OH})_2$ remains close to the anode; and during charge, the $\text{Cd}(\text{OH})_2$ at the anode reverts to $\text{Cd} + \text{H}_2\text{O}$ as the cathode releases 2H^+ per Cd^{2+} ion to the electrolyte. At the end of charge, all the Cd^{2+} ions are reduced back to Cd and all the nickel is present as Ni(III). The Ni(IV)/Ni(III) couple cannot be accessed with a further increase in the charging voltage; instead, the electrolyte is oxidized:



This cell was the first rechargeable battery to be used in handheld devices.

With a suitable gelling agent to passivate carefully sized Zn particles, a $\text{Zn}/\text{KOH}/\text{NiOOH}$ secondary battery may be marketed.

The *metal hydride–nickel cell*, $\text{MH}_x/\text{KOH}/\text{NiOOH}$, also makes use of the NiOOH cathode; it replaces the Cd anode with a metal hydride, MH_x insertion alloy having its Fermi energy E_{FA} , like that of Cd, well-matched to the LUMO of the aqueous KOH electrolyte. However, the H^+ -ion diffusivity in the hydride is slower than that in the gelatinous $\text{Cd}(\text{OH})_2$, so it has a poorer rate capability at lower temperatures. On the other hand, it eliminates the heavy, toxic Cd to give a higher energy density (Wh/kg) and provides a safe power source for electric vehicles. However, a $\text{Zn}/\text{KOH}/\text{NiOOH}$ cell of good cycle life may prove competitive.

Nonaqueous Electrolytes for Li-Ion Secondary Batteries

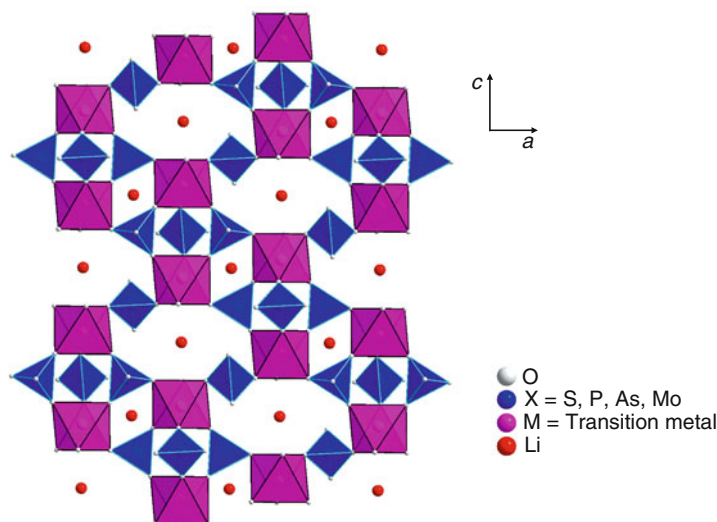
The demand for a rechargeable battery with a greater specific energy requires a higher output voltage and therefore an electrolyte with a larger window E_g between its LUMO and HOMO than the 1.23 eV of an aqueous electrolyte. Since H^+ ions are not mobile over an appreciable temperature range above and below 20°C in the absence of water, the Li^+ and Na^+ ions are the next logical candidates for the working ion.

Early work with Na^+ ions concentrated on solid electrolytes. Although solid electrolytes have a large window, they do not retain a large-area interface with a solid electrode that changes its volume significantly with the state of charge of the battery. Although all solid-state microbatteries are made, a solid electrolyte preferably contacts a liquid, either a liquid electrode or a liquid electrolyte. The sodium–sulfur battery uses liquid electrodes and operates above 300°C [2]. On the other hand, a composite electrolyte having a solid-electrolyte separator and different liquid electrolytes either side, as in the Li/seawater primary battery, can provide a feasible room-temperature secondary battery [3]. For example, the Li^+ -ion solid-electrolyte $\text{Li}_{1.3}\text{Ti}_{1.7}\text{Al}_{0.3}(\text{PO}_4)_3$ with the framework structure of hexagonal $\text{Fe}_2(\text{SO}_4)_3$, Fig. 8, can have interstitial Li giving $\sigma_{\text{Li}} > 10^{-4}$ S/cm at 20°C [4]. Rechargeable batteries based on this strategy are now being investigated. However, this commercially available inorganic solid electrolyte contains Ti(IV), which is too easily reduced. Another solid electrolyte with a $\sigma_{\text{Li}} > 10^{-4}$ S/cm needs to be identified.

A solid polymer electrolyte can retain contact over a large surface area of a solid electrode provided the changes in electrode volume with state of charge of a cell are modest. Polyethylene oxides (PEOs) containing a lithium salt are low-cost, nontoxic,

Li^+ -ion electrolytes with good chemical stability [5], but a $\sigma_{\text{Li}} < 10^{-5}$ S/cm at 20°C is too low for a power battery and the HOMO versus Lithium is below 4.0 V. The introduction of the oxide particles Al_2O_3 , TiO_2 , SiO_2 , or ZrO_2 creates a more amorphous polymer matrix by inhibiting chain crystallization and attracting Li^+ from its salt; the result is an enhanced σ_{Li} and Li^+ -ion transference number $t = \sigma_{\text{Li}}/\sigma$, where σ is the total anion plus Li^+ -ion conductivity; but σ_{Li} is still not comparable to that of the best liquid electrolytes, [6]. Therefore, most attention has been given to Li^+ -ion batteries containing liquid electrolytes.

The most widely used liquid electrolytes consist of Lithium salts dissolved in organic carbonates: propylene carbonate (PC), dimethyl or diethyl carbonate (DMC or DEC), ethyl methyl carbonate (EMC), and mixtures of DMC or DEC with ethylene carbonate (EC). The EC component provides a passivating SEI layer on a carbon anode where the E_{FA} of the anode lies above the LUMO of the carbonates, which is about 1.1 eV below the E_{FA} of Lithium. The carbonates are reasonably good solvents for Li salts and they have a relatively low viscosity, which results in a low activation energy for Li^+ -ion diffusion to give a $\sigma_{\text{Li}} > 10^{-3}$ S/cm at 20°C and a ready penetration into a porous electrode. The HOMO is about 4.3 eV below the E_{FA} of Lithium, which gives an electrolyte



Battery Components, Active Materials for. Figure 8

NASICON (NA Superlionic CONductor) framework structure, which is the same as that of hexagonal $\text{Fe}_2(\text{SO}_4)_3$

window $E_g \approx 3.7$ eV. A carbonate electrolyte decomposes at a voltage $V > 4.9$ V versus Lithium; an SEI layer can stabilize the Ni, Mn oxides with cathode voltages in the interval $4.3 < V < 4.9$ V, but at the expense of a larger activation energy for Li^+ -ion transfer across it. However, this ΔH_m can be reduced either by doping to remove Ni from the surface or by coating the particles with a thin layer of a mixed Li^+ -ion/electronic conductor that replaces the SEI layer and is not removed by the volume changes that accompany charge/discharge cycling. With this strategy, an effective electrolyte window $E_g^{\text{eff}} \approx 3.8$ eV can be created. However, organic electrolytes are flammable, which raises safety concerns where an SEI layer is formed on the anode. Ionic liquids are not flammable and have a larger window, but they are too viscous to be practical unless they are blended with a less viscous liquid. Carbonate-ionic liquid blends that are not flammable have been demonstrated, but they are more viscous than a pure liquid carbonate and the carbonate component determines the operative electrolyte window. The loss of rate capability must be weighed against the nonflammable property in any blend of a carbonate with an ionic liquid.

Alternatively, the salt LiAlCl_4 dissolved in the inorganic liquid SO_2 has been proposed [7]; this Li^+ -ion electrolyte has a good room temperature $\sigma_{\text{Li}} = 7 \times 10^{-2}$ S/cm and is nonflammable; its electrolyte window may be too small to be competitive with the carbonates, but it deserves to be explored for Li batteries of lower voltage.

Insertion Compounds for Li-Ion Secondary Batteries

Anodes with Li^+ -Ion Liquid Electrolytes

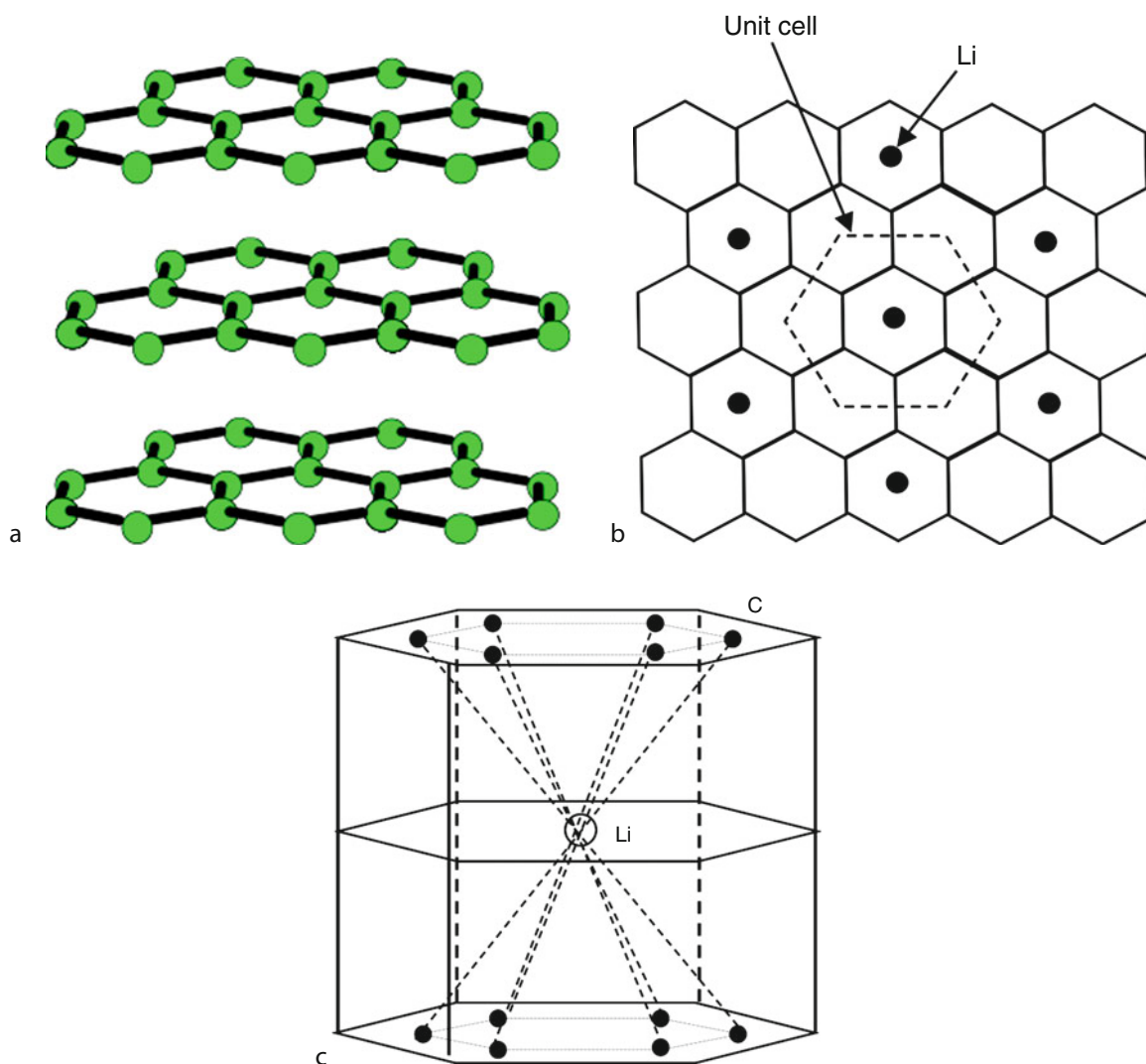
In a liquid-carbonate electrolyte, dendrites form on an elemental Lithium anode that can grow across the electrolyte to short-circuit a cell on repeated cycling. Therefore, carbon or an alloy buffered by carbon is used with a liquid electrolyte [8].

Graphite has the layered structure of Fig. 9a and Li can be inserted rapidly and reversibly between the layered sheets to create sites capped by six C atoms and form LiC_6 , Fig. 9b, c. Similar reactions with graphitic sheets occur for the several different forms of carbon; but with a 2D insertion that shifts neighboring

graphene sheets relative to one another, a more amorphous type of carbon is preferred over large crystallites of graphite. A carbon anode into which Li^+ ions from the cathode are inserted on an initial charge, Eq. 12, is commonly used in Li^+ -ion rechargeable batteries. However, the E_{FA} of the reduced carbon in LiC_6 lies above the LUMO of a carbonate electrolyte, so on the initial charge it consumes irreversibly Li^+ ions from the cathode in the formation of a non-blocking SEI layer on the carbon unless the SEI layer is formed on the anode before battery assembly. Moreover, if a fast charge raises the charging voltage above Li^+/Li^0 , Lithium is plated out on the SEI layer, which introduces the possibility of dendrite formation with a catastrophic short circuit within the cell after repeated cycling. This problem limits the rate of charge unless the E_{FA} is at least 0.5 eV below Li^+/Li^0 . With a carbon anode at ca. 0.2 V vs Li^+/Li^0 , this problem introduces complexity in the safety management of a Li^+ -ion battery with a flammable electrolyte. To eliminate irreversible capacity loss due to SEI formation on the initial charge and to increase the rate of charge while simplifying safe battery management, it is necessary to introduce an insertion-compound anode giving a voltage versus Lithium greater than 1.0 V, but preferably less than 1.5 V. The spinel $\text{Li}_4\text{Ti}_5\text{O}_{12}$ gives a constant voltage versus Lithium of $V = 1.5$ V, but its capacity is disappointing. Preliminary studies have shown a layered niobate having a single-phase solid-solution Li insertion between 1.2 and 1.6 V versus Lithium has a higher capacity than that of $\text{Li}_4\text{Ti}_5\text{O}_{12}$, a good rate capability, and a promising cycle life; but Nb is more expensive than Ti and a fully satisfactory, safe anode material has yet to be accepted. The secondary Li^+ -ion batteries using a liquid electrolyte are therefore identified by their insertion-compound cathode. The Li^+ ion is small enough to be inserted into the interstices of a close-packed anion array.

Cathodes with Li-Ion Liquid Electrolytes

Layered Sulfides [9]. The MS_2 ($M = \text{Ti}, \text{V}, \text{V}_{0.5}\text{Cr}_{0.5}$) sulfides have the layered structure of Fig. 10 in which strongly bonded sheets of edge-shared $\text{MS}_{6/3}$ octahedra are held together by weak Van der Waals bonds. In the late 1960s, it was reported that Li can be intercalated (inserted) reversibly between the TiS_2 layers to give the

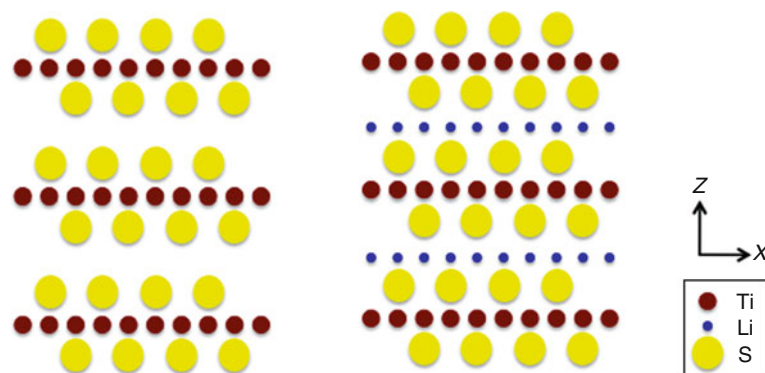


Battery Components, Active Materials for. Figure 9
Structure of (a) graphite, (b) graphene stacking in LiC_6 , and (c) LiC_6

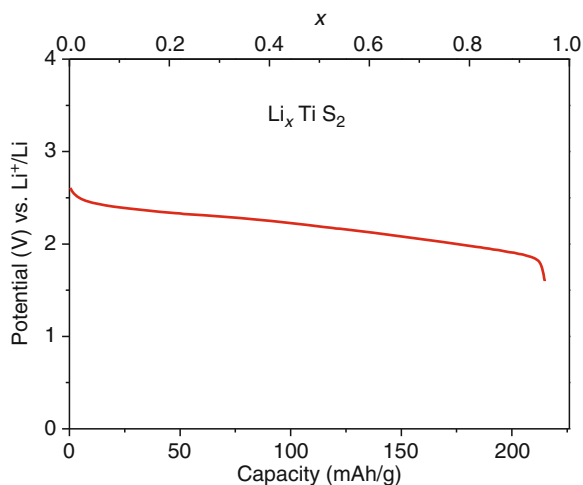
solid-solution reaction Li_xTiS_2 ($0 \leq x \leq 1$) with the voltage profile of Fig. 11 for a Li/LiClO_4 in PC/TiS_2 cell. However, catastrophic failures due to dendrite formation on the Lithium anode forced consideration of an anode that would lower the cell voltage to where the cell would not be competitive with secondary cells having an aqueous electrolyte. Nevertheless, this early report raised awareness that the designer of a cathode material for a Li^+ -ion rechargeable battery should look to insertion compounds capable of providing a larger voltage versus Lithium than 2.5 V. However, the designer must not only identify a host structure into/

from which Li can be inserted/extracted reversibly, but also consider the limiting E_{FC} of the host structure and whether its E_{FC} can be matched to the HOMO of the electrolyte. For this latter consideration, it is instructive to consider the limiting E_{FC} of a layered sulfide.

Figure 12a illustrates schematically the energy density of one-electron states of TiS_2 versus their energy ϵ relative to the E_{FA} of a Lithium anode. The outer s and p electrons of the Ti and S atoms are primarily involved in the strong Ti–S bonding. The ionic and covalent components of this bonding create a filled broad band of one-electron states that have a primarily S-3 p



Battery Components, Active Materials for. Figure 10
Layered TiS_2 and LiTiS_2 structures

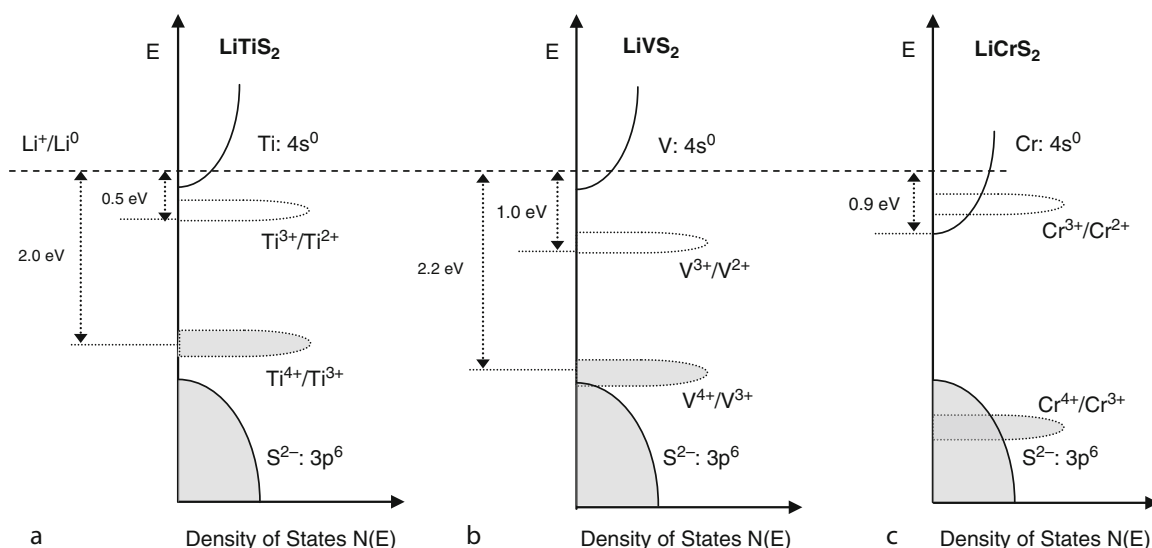


Battery Components, Active Materials for. Figure 11
 $V(x)$ versus Lithium profile for Li_xTiS_2 and $\text{Li}_{2x}[\text{Ti}_2]\text{S}_4$,
 $0 \leq x \leq 1$

character separated by an energy gap from an empty broad band of states that have a primarily Ti-4s character. These bands have similar energies in all the MS_2 layered compounds, but the bottom of the M-4s band falls progressively with increasing atomic number of the M atom. Empty Ti-3d states lie in the energy gap between these two bands. The cubic component of the site symmetry of a Ti(IV) cation splits the σ -bonding and π -bonding 3d orbitals by an energy Δ_c ; the σ -bonding states, not shown, lie above the bottom of the Ti-4s band and the π -bonding states lie in the energy gap between the broad Ti-4s and S-3p bands.

The trigonal component of the site symmetry splits the π -bonding 3d states into a lower, orbitally nondegenerate a_1 band and a higher, orbitally two-fold-degenerate e_π band. The Fermi energy of stoichiometric TiS_2 lies in a small energy gap between the bottom of the Ti- a_1 band and the top of the S-3p bands. Intercalation of Li^+ ions is neutralized by electrons entering the Ti- a_1 band; as E_{FC} rises with x in Li_xTiS_2 , the voltage versus Lithium drops smoothly in this single-phase solid-solution reaction, Fig. 11. The $\text{Ti}^{4+}/\text{Ti}^{3+}$ couple of Fig. 12a actually lies in an itinerant-electron a_1 band that is half-filled in LiTiS_2 ; however, displacement of Li to the tetrahedral sites of the Li layer in $\text{Li}_{1+x}\text{TiS}_2$ raises the $\text{Ti}^{3+}/\text{Ti}^{2+}$ couple to just below the Ti-4s band.

As the atomic nuclear charge increases from Ti to V to Cr, the 3d electrons become more tightly bound to the nucleus, which lowers their energies. The E_{FC} of VS_2 is pinned at the top of the S-3p bands, Fig. 12b. Pinning of E_{FC} occurs because, as the cation- d -like states move from above to below the top of the bonding anion- p bands, the empty antibonding states remain above the anion- p bonding states; but the empty antibonding states change their character from primarily cation- d to primarily anion- p while retaining their d -orbital symmetry. On the other hand, if the cation- d states fall too far below the top of the anion- p bands, the holes in the antibonding states become trapped in purely anion- p antibonding states of a S-S bond to create the $(\text{S}_2)^{2-}$ ion. The Cr(IV) formal valence state cannot be accessed because a localized-electron Cr(IV)/Cr(III) redox couple lies too far below the top of the



Battery Components, Active Materials for. Figure 12

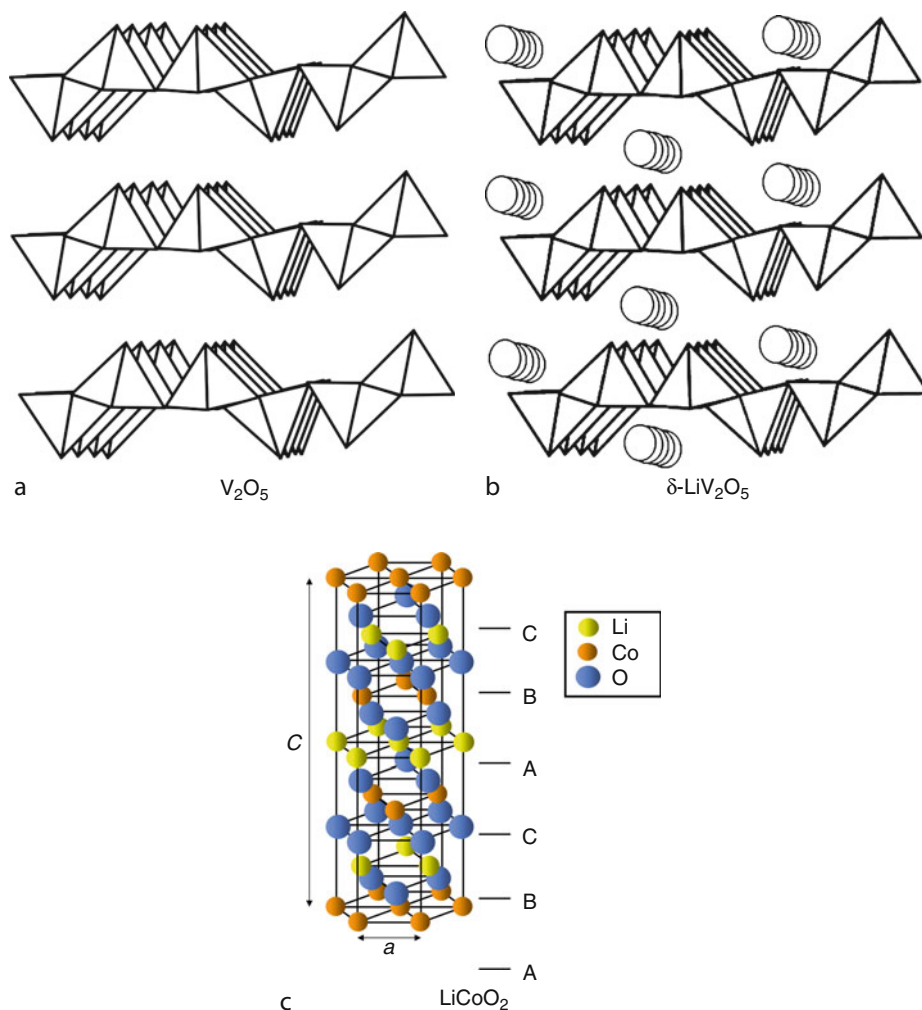
Energies of the bottom of the 4s band, the top of the S-3p bands, and π -bonding d-electron energies relative to the E_{FA} of Lithium for TiS_2 , VS_2 , and LiCrS_2 . In $\text{Li}_{1+x}\text{MS}_2$, all the Li occupy tetrahedral sites of the Li layer and the M(III)/M(II) levels are raised to give $V = 0.5$ V and 1.0 V, respectively, for $\text{Li}_{1+x}\text{TiS}_2$ and $\text{Li}_{1+x}\text{VS}_2$; the Cr(III)/Cr(II) level is raised above the bottom of the 4s band so that Li insertion into CrS_2 displaces Cr^0

S-3p bands. However, $\text{V}_{0.5}\text{Cr}_{0.5}\text{S}_2$ can be stabilized in the layered MS_2 structure, and reduction of this host by the intercalation of Li into $\text{Li}_x\text{V}_{0.5}\text{Cr}_{0.5}\text{S}_2$ accesses the V(V) to V(III) formal valences [10]. A flat $V \approx 2.7$ V for $x < 0.5$ in $\text{Li}_x\text{V}_{0.25}\text{Cr}_{0.75}\text{S}_2$ signals that the top of the S-3p bands is about 2.7 eV below the E_{FA} of Lithium. This limitation on the voltage in these sulfides motivated study of the extraction of Li from similarly layered oxides since the top of the O-2p bands would be below the top of the S-3p bands.

Layered Oxides. Most solid cathode hosts are transition-metal oxides in which E_{FC} lies in either a mixed-valent redox couple or a narrow band of d-electron states. The PbO_2 cathode of the lead–acid battery is an exception; its E_{FC} is located in a narrow Pb-6s band well-separated from the broad, empty Pb-6p band because Pb is heavy.

A layered transition-metal MO_2 oxide analogous to TiS_2 does not exist; the electrostatic repulsive forces between the oxygen layers are stronger than any Van der Waals bonding, which is much weaker in an oxide than in the chalcogenides. However, where the transition-metal M atom has no d electrons, or at most one d

electron, and is too small to be stable in an octahedral site, it may undergo a ferroic M-atom displacement to form a short $\text{M} = \text{O}$ bond with one oxygen of the octahedral site and a long $\text{O} \cdots \text{M}$ bond on the opposite side. These displacements create site dipoles that can stabilize a layered oxide as is illustrated by the structure of V_2O_5 , Fig. 13a. On the other hand, several LiMO_2 oxides form rock-salt structures in which the Li^+ and M(III) ions occupy alternate layers of M(III) octahedral sites, Fig. 13c. The sheets of edge-shared $\text{MO}_{6/3}$ octahedra are analogous to those of TiS_2 , but the stacking between sheets gives hexagonal-close-packed sulfide ions in TiS_2 , cubic-close-packed oxide ions in LiMO_2 . The layers can also be stacked to give trigonal-prismatic sites between the layers. Moreover, Li can be either extracted, $\text{Li}_{1-x}\text{MO}_2$, or inserted, $\text{Li}_{1+x}\text{MO}_2$. Insertion of more than one Li per formula unit displaces Li^+ ions from octahedral to tetrahedral sites in the Li layer to form Li_2MO_2 in a two-phase reaction. The two-phase insertion reaction LiVS_2 – Li_2VS_2 gives a voltage of 1.0 V versus Lithium, and an SEI layer is formed on the electrode. The $\text{Li}_{1-x}\text{MO}_2$ oxides are of interest as cathodes.



Battery Components, Active Materials for. Figure 13
The structures of (a) V_2O_5 , (b) $\delta\text{-LiV}_2O_5$, and (c) $LiMO_2$

Extraction of Li from $LiMO_2$ oxides creates $M(IV)/M(III)$ mixed valence on the M atoms. Where the M atoms have a localized spin S associated with a cation configuration $3d^n$, the mobile electron of the mixed-valent system moves diffusively in a hopping transfer $d^{n+1} + d^n = d^n + d^{n+1}$ between like atoms on equivalent lattice sites. In this case, the d^n/d^{n+1} configuration of an $M(IV)/M(III)$ mixed-valent system may be considered a redox couple because the time for a hop is long compared to the period of a lattice vibration that traps the mobile electron or hole at a single site. Where the empty d -electron states lie close to the top of an anion- p band, the electrons may occupy a narrow

band of itinerant-electron states as in TiS_2 and VS_2 . Electrons in a partially filled band of itinerant-electron states give a metallic conductivity, those in redox couples require an activation energy for a hop to a like neighbor.

The energies of successive redox couples, for example, $M(IV)/M(III)$ to $M(III)/M(II)$, are separated by an on-site electron–electron electrostatic repulsive energy. In the case of $Cr(III)$ in Fig. 12c, the cubic crystal-field splitting is added to this electrostatic on-site energy to raise the $Cr(III)/Cr(II)$ energy to above the bottom of the Cr -4s band while the $Cr(IV)/Cr(III)$ couple lies below the top of the S -3p bands. Insertion of Li into

LiCrS_2 results in $\text{Li}_2\text{S} + \text{Cr}^0$; extraction of Li results in $(\text{S}_2)^{2-}$ formation. On the other hand, the electrons in the narrow $V-a_1$ band with E_{FC} pinned at the top of the $S-3p$ bands allows access to both the $V(V)/V(IV)$ and $V(IV)/V(III)$ mixed-valence states without any energy gap between them [10].

The Co(III) ions in LiCoO_2 are in their low-spin $S = 0$ state, but the initial Co(IV) ions appearing on removal of Li in $\text{Li}_{1-x}\text{CoO}_2$ are in their high-spin $S = 5/2$ state [11]; the holes are trapped at a single Co(IV) site. However, in the range $0.05 \leq x \leq 0.45$, the voltage is flat at $V \cong 4.0$ V versus Lithium, which signals a two-phase reaction between a Li-rich phase containing high-spin Co(IV) and a Li-poor phase containing low-spin Co(IV/III) ions with holes in an itinerant-electron π^* band [12]. For $x \geq 0.55$, a new phase with different stacking of the CoO_2 sheets begins to appear as oxygen is evolved and/or H^+ ions from the organic electrolyte are inserted so as to retain the $\text{Co(IV)}/\text{Co}$ ratio at about 0.45 [13]. The outgassing of oxygen shows that the holes in the π^* band have sufficient $\text{O-}2p$ character, at least at a grain surface, to become trapped in peroxide ions $(\text{O}_2)^{2-}$ followed by $2(\text{O}_2)^{2-} = 2\text{O}^{2-} + \text{O}_2\uparrow$. Clearly, the $\text{Li}_{1-x}\text{CoO}_2$ electrode reaches its *intrinsic limit* at a ratio $\text{Co(IV)}/\text{Co} \approx 0.45$; this limit is above the HOMO of the electrolyte, so the electrolyte is not being decomposed aside from loss of inserted H^+ ions. The intrinsic limit restricts the practical capacity of $\text{Li}_{1-x}\text{CoO}_2$ to only 50% of the theoretical capacity, that is, to a $Q = 140$ mAh/g.

A cell with a carbon anode forms an LiC_6 phase during an initial charge from the discharged cathode LiCoO_2 , and formation of an SEI layer on the reduced carbon during the initial charge reduces further the available capacity of the cell unless the SEI layer on the anode is formed before the cell assembly. Moreover, by fabricating the cell with a discharged cathode, it is the capacity of the cathode that determines the capacity of the cell. Nevertheless, the E_{FA} of the carbon anode is only 0.2 eV below the E_{FA} of Lithium, so the cell has a high specific energy QV because of its $V \approx 3.8$ V. The cell also has a high volumetric energy density, which is why it captured the market for laptop computers, cell telephones, and other handheld devices. The *tap density* of an electrode refers to the density of active particles that can be packed into a given volume, and a high tap

density of LiCoO_2 is responsible for the high volumetric energy density.

Cobalt is expensive and toxic, so it was natural to try substitution of Ni for Co. However, it proves difficult to prepare well-ordered LiNiO_2 . The maximum Ni substitution for Co in a layered phase with well-ordered Li^+ ions is $\text{LiCo}_{0.15}\text{Ni}_{0.85}\text{O}_2$ [14]. Since the holes in $\text{Li}_{0.5}\text{CoO}_2$ occupy a π^* band whereas those on low-spin Ni(III) occupy a σ^* band of higher energy, the $\text{LiCo}_{0.15}\text{Ni}_{0.85}\text{O}_2$ system gives a loss of O_2 and/or H^+ insertion only for $(1-x) < 0.35$, which gives a $Q = 200$ mAh/g. Addition of a small amount of Al in $\text{LiAl}_{0.05}\text{Co}_{0.15}\text{Ni}_{0.8}\text{O}_2$ improves the ordering of the Li and optimizes the cyclability of this cathode.

The transfer of M atoms into vacant sites of the Li layer on Li extraction requires their transfer via a tetrahedral site of the interstitial space. The low-spin Co(IV/III) and Ni(IV/III) cations have a strong octahedral-site preference, so transfer to the vacancies in the Li layer is kinetically inhibited below 300°C . However, ions like Fe(III) , Mn(II) , and Cr(VI) have a strong tetrahedral-site preference and are easily displaced to the interstitial tetrahedral sites on Li removal. Therefore, LiFeO_2 does not retain its structure on Li extraction. The disproportionation reactions $2\text{Mn(III)} = \text{Mn(II)} + \text{Mn(IV)}$ and $3\text{Cr(IV)} = 2\text{Cr(III)} + \text{Cr(VI)}$ introduce Mn(II) and Cr(VI) ions into the interstitial space to block insertion of Li back into the structure. Therefore, in order to eliminate Co and to take advantage of the pinning of the $\text{Ni(IV)}-\text{Ni(II)}$ valence states at the top of the $\text{O-}2p$ bands, the $\text{LiNi}_{0.5}^{(\text{II})}\text{Mn}_{0.5}^{(\text{IV})}\text{O}_2$ structure was investigated [15]; the Mn(IV) ion has a strong octahedral-site preference and the $\text{Mn(V)}/\text{Mn(IV)}$ redox couple lies well below the top of the $\text{O-}2p$ bands where the disproportionation reaction $3\text{Mn(IV)} = 2\text{Mn(III)} + \text{Mn(VI)}$ is inhibited. However, the mean size of the Ni(II) and Mn(IV) ions is too large for good ordering of the Li^+ ions in $\text{Li}(\text{Ni}_{0.5}\text{Mn}_{0.5})\text{O}_2$ to be easily obtained. Therefore, considerable attention has been given to $\text{Li}(\text{Ni}_{0.5-x}\text{Co}_{2x}\text{Mn}_{0.5-x})\text{O}_2$ with $x \leq 1/6$ where the $\text{Ni(III)}/\text{Ni(II)}$ and $\text{Ni(IV)}/\text{Ni(III)}$ mixed valences are accessed without a step in the voltage profiles on passing from one to the other because of E_{FC} pinning. Moreover, solid solutions of these LiMO_2 oxides with $\text{Li}(\text{Li}_{1/3}\text{Mn}_{2/3})\text{O}_2$, commonly designated Li_2MnO_3 , as a randomly intercalated second phase exhibit, after an

initial charge, a high reversible capacity of 250 mAh/g even though Li_2MnO_3 itself is not electrochemically active [16]. The voltage profiles of these solid solutions exhibit two distinct regions during the first charge, an initial sloping range corresponding to the oxidation of the Ni(II) to Ni(IV) and the Co(III) to Co(IV) followed by a plateau at $V \approx 5.5$ V. The plateau at 4.5 V appears to signal oxidation of the electrolyte. The excess Li_2MnO_3 increases the Mn(IV) concentration, which lowers further the top of the O-2- bands and thus increases the intrinsic voltage limit of the layered oxide. The passivating SEI layer formed from the electrolyte at voltages $V > 4.3$ V inhibits Li^+ -ion transfer across the electrode/electrolyte interface, but coating with an oxide layer that transports Li^+ ions suppresses formation of the electrolyte SEI layer to allow fast cycling. Nevertheless, these layered oxides must compete against spinel cathodes containing Ni(II) and Mn(IV).

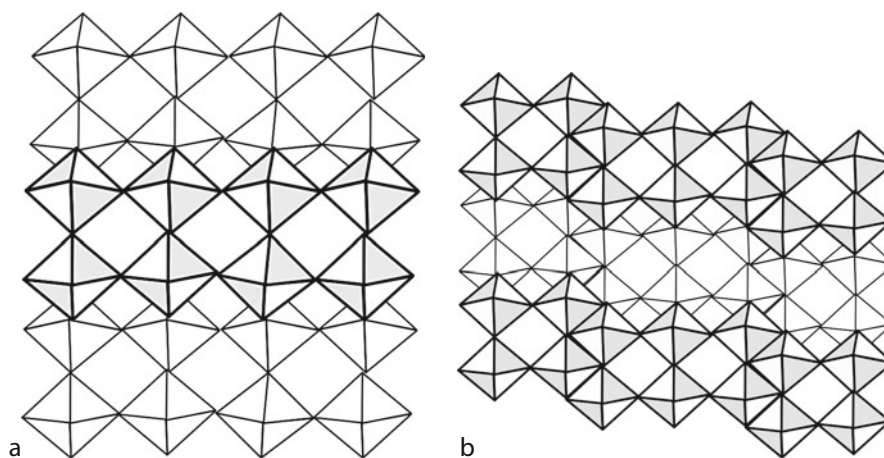
Vanadium Oxides. Several intermediate phases appear between V_2O_3 and V_2O_5 ; Li insertions into V_2O_5 and V_6O_{13} were investigated in the 1970s, and an amorphous or low-crystallinity VO_x with a polyethylene oxide (PEO) electrolyte is used in a Li/PEO/ VO_x secondary battery for stationary storage of electrical energy [17].

Figure 13a shows the structure of orthorhombic V_2O_5 ; corner-shared paired chains of distorted VO_6 octahedra parallel to the c -axis share edges to create

c -axis zigzag chains. Ferroic c -axis displacements of V atoms in the paired chains create asymmetric c -axis bonds $0 \dots V = O$, which places the V atoms in square-pyramidal sites. These chains share corners in the $a-b$ planes with antiferroelectric coupling across shared edges to create the $a-b$ layers of Fig. 13a. Li^+ ions can be inserted reversibly into the b -axis tunnels to form $\delta\text{-LiV}_2\text{O}_5$ via an intermediate $\varepsilon\text{-Li}_x\text{V}_2\text{O}_5$ phase.

In the range $0 \leq x \leq 1$ of $\text{Li}_x\text{V}_2\text{O}_5$, reduction of the vanadium on Li^+ -ion insertion only tilts the square-pyramidal sites of the $a-b$ planes, but three phases can be distinguished: α ($0 \leq x \leq 0.1$), ε ($0.35 \leq x \leq 0.7$), and δ ($0.9 \leq x \leq 1.0$). The reversible insertion of Li into V_2O_5 gives a voltage profile versus Lithium with two plateaus, one at 3.4 V for the $\alpha + \varepsilon$ range $0.1 \leq x \leq 0.35$ and the other at 3.2 V for the $\varepsilon + \delta$ range $0.7 \leq x \leq 0.9$. On further Li insertion, the voltage drops abruptly to 2.4 V followed by a monotonic decrease with x to about 1.5 V over the range $1 < x < 3$. Cycling through the first-order transition at $x = 1$ damages the crystallites and lowers the cyclability. However, insertion into amorphous or low-crystallinity V_2O_5 allows faster and better cyclability. Insertion of 1.5 Li per V atom gives a relatively large capacity.

The structure of V_6O_{13} shows how the particles of low-crystallinity or amorphous VO_x can accommodate Li^+ -ion insertion into 1D tunnels. Figure 14 shows the structures of V_2O_5 and V_6O_{13} projected, respectively, onto its (001) and (010) plane, which illustrates how



Battery Components, Active Materials for. Figure 14

Comparison of structures of V_2O_5 projected onto its (001) plane and V_6O_{13} onto its (010) plane

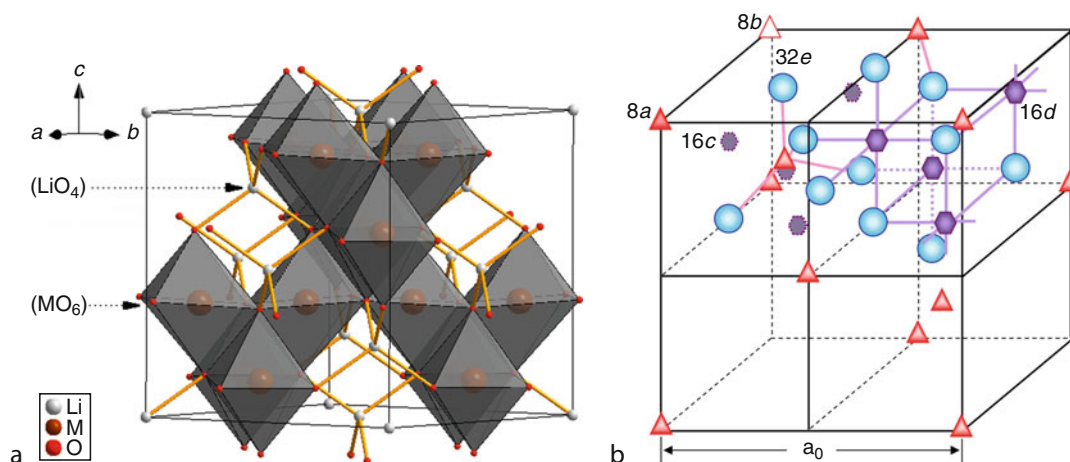
the V_6O_{13} structure can be derived from that of V_2O_5 . Removal of oxygen from every third a – c oxygen plane of V_2O_5 is followed by a shear, which leaves tunnels for Li^+ -ion insertion as in V_2O_5 . The shear planes need not be ordered as in V_6O_{13} .

These observations have led to the synthesis of a two-dimensional (2D) pseudocrystalline phase containing segments of three planes similar to those of V_2O_5 that are displaced from one another by a slip plane. This structure provides an insertion of up to two Li atoms per formula unit with a monotonic voltage decrease with x , except for a small step at $x = 1.5$, over the voltage range $2.5 < V < 3.4$ V versus Lithium. Nevertheless, there is a gradual capacity fade with cycle number.

The voltage profile of $Li_xV_6O_{13}$ shows small steps at $x = 1, 2$, and 3 as the voltage decreases from 2.8 to 2.4 V versus Lithium and a drop from 2.4 to 2.1 V in the interval $3 < x < 4$ that is followed by a gradual drop to 2.0 V as x approaches 6 . The steps appear to correspond to Li^+ -ion ordering with electrons entering $V - 3d$ bands rather than localized redox couples; the electronic states change character from $V - 3d$ with a large $O - 2p$ component to a dominant $V - 3d$ character with increasing x . Capacity fading on cycling makes this material not competitive as a cathode for a secondary battery.

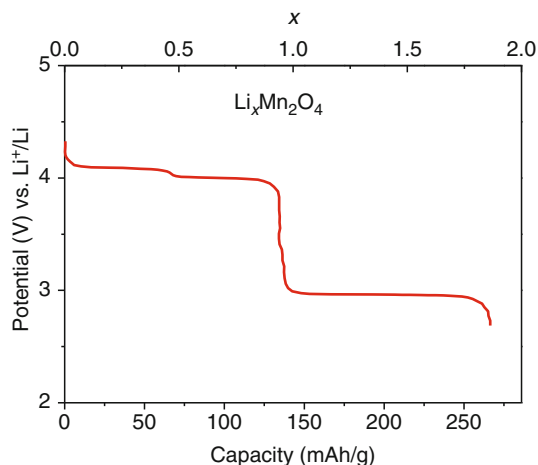
Spinel. The $A[M_2]O_4$ spinels have a cubic-close-packed array of oxygen atoms with M-site cations in half of the octahedra, the $16d$ sites of space group $Fd\bar{3}m$ of Fig. 15. The $[M_2]O_4$ array represents a strongly bonded framework with A atoms in the interstitial tetrahedral sites $8a$. The empty $16c$ octahedral sites share faces with the $8a$ sites to form, with the $8a$ sites, a 3D-interconnected interstitial space. On Li^+ -ion insertion into an empty $16c$ site, the coulombic repulsive force between the Li^+ -ion and the near-neighbor A-site cations pushes all the A-site cations in a cascade into the $16c$ sites [18].

In the case of magnetite, $Fe[Fe_2]O_4$, insertion of one Li per formula unit produces an ordered rock-salt array with Fe remaining on all the $16d$ sites and Li and Fe randomly distributed over the $16c$ sites. Further insertion of Li extrudes Fe reversibly from the $16c$ sites to form the ordered rock-salt structure $Li_2[Fe_2]O_4$ and amorphous Fe^0 . From this observation, it was clear that Li insertion into the system $Li_{1+y}[Mn_2]O_4$ ($0 < y \leq 1$) would place Li^+ ions in the octahedral $16c$ sites and Li extraction in the system $Li_{1-y}[Mn_2]O_4$ ($0 < y \leq 1$) would leave the Li^+ ions in tetrahedral $8a$ sites. Moreover, with only Li^+ ions in the 3D interstitial space, a fast Li^+ -ion transport could be anticipated. The voltage profile of Fig. 16 for the system $Li_x[Mn_2]O_4$, $0 \leq x \leq 2$, shows a 1-V step at $x = 1$ where the Li^+ ions



Battery Components, Active Materials for. Figure 15

(a) The structure of a cubic $A[M_2]O_4$ spinel showing quadrants of edge-shared $MO_{6/3}$ octahedra alternating with quadrants of tetrahedral-site A cations on traversing the $\langle 100 \rangle$ axes. (b) Two quadrants of the cubic spinel structure showing the diamond array of the A-site sublattice $8a$; M cations are in $16d$ and oxygen in $32e$



Battery Components, Active Materials for. Figure 16
The $V(x)$ versus Lithium profile for $\text{Li}_x[\text{Mn}_2]\text{O}_4$ showing a 1 eV step in the M(IV)/M(III) redox couple at $x = 1$

shift from tetrahedral to octahedral sites. This remarkable 1-eV shift in the energy of the Mn(IV)/Mn(III) couple shows that the energy of an active redox couple is sensitive to the Madelung ionic electrostatic energy of the oxide.

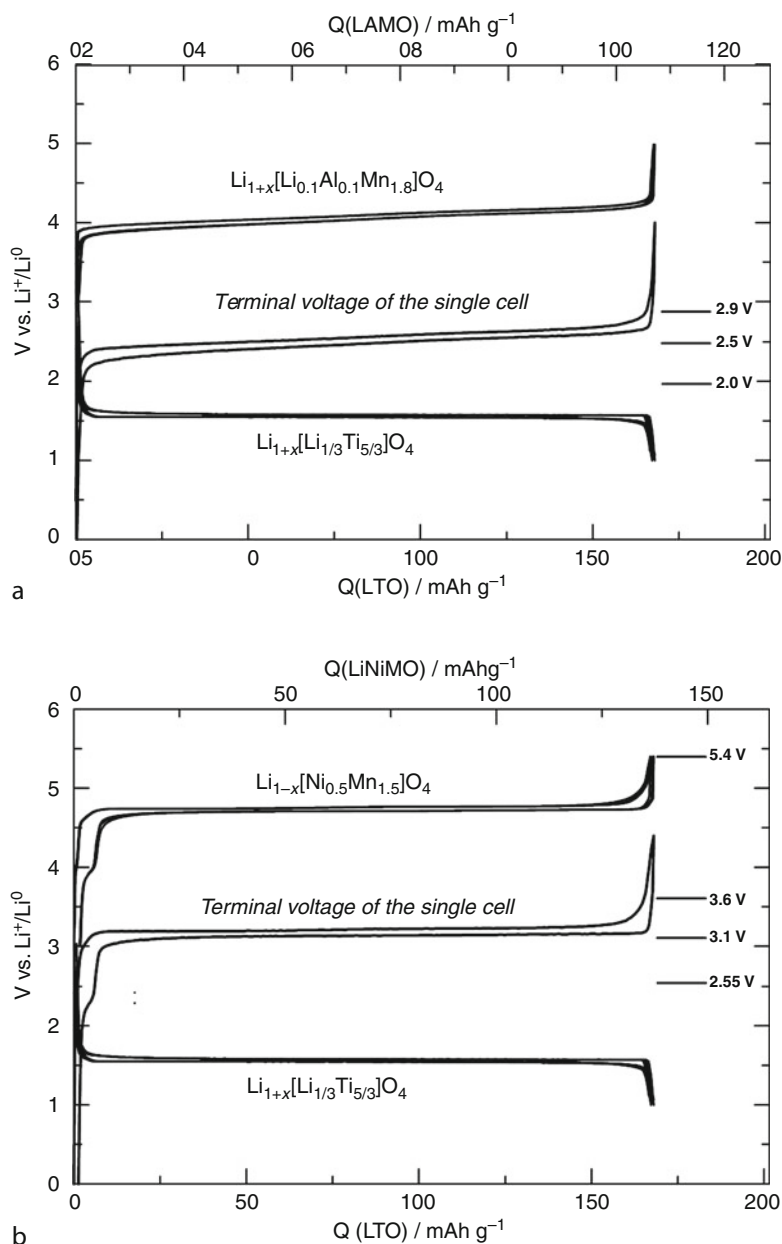
In contrast, the voltage profile of Li insertion into the thiospinel framework $[\text{Ti}_2]\text{S}_4$ shows no step at $x = 1$ [19]; the profile of $\text{Li}_x[\text{Ti}_2]\text{S}_4$, $0 \leq x \leq 2$, is nearly identical to that for the layered system Li_xTiS_2 , which shows that the Li^+ ions occupy only octahedral 16c sites for all x in $\text{Li}_x[\text{Ti}_2]\text{S}_4$. Preparation of the thiospinel $\text{Li}[\text{Ti}_2]\text{S}_4$ is not straightforward; the thiospinel framework $[\text{Ti}_2]\text{S}_4$ is prepared by chemical extraction of tetrahedral-site Cu^+ from the thiospinel $\text{Cu}[\text{Ti}_2]\text{S}_4$. In both the layered TiS_2 and the spinel framework $[\text{Ti}_2]\text{S}_4$, the octahedral $\text{TiS}_{6/3}$ sites share only edges, not corners, with neighboring $\text{TiS}_{6/3}$ sites; only the shape of the interstitial space has been changed from 2D to 3D. The 2D interstitial space of LiTiS_2 allows intercalation of other species than the Li^+ ions whereas the 3D interstitial space of the strongly bonded spinel framework does not.

The 1-V step in the voltage profile of $\text{Li}_x[\text{Mn}_2]\text{O}_4$ limits the capacity of this spinel to one Li^+ per two Mn atoms at either 3.0 V or 4.0 V versus Lithium. The flat 3.0 V plateau reflects a cubic to tetragonal transition of the $[\text{Mn}_2]\text{O}_4$ framework due to a cooperative Jahn–Teller site distortion where more than half of the 16d sites are occupied by Mn(III) ions. Octahedral-site,

high-spin Mn(III) ions have a localized spin $S = 2$ with one electron occupying an orbitally twofold-degenerate pair of σ -bonding e_σ orbitals; a site distortion to tetragonal symmetry removes the degeneracy, stabilizing an occupied ($3z^2 - r^2$) orbital at the expense of an empty ($x^2 - y^2$) orbital of the e_σ pair. A cooperative site distortion minimizes the elastic energy per site that it costs to distort a site from cubic symmetry.

The 8a sites consist of two interpenetrating face-centered-cubic arrays to form the diamond lattice. The small step in the 4.0-V plateau of Fig. 16 reflects an ordered $\text{Li}_{0.5}[\text{Mn}_2]\text{O}_4$ phase in which the Li^+ ions occupy only one of the two interpenetrating face-centered-cubic 8a arrays; two-phase separations occur either side of $x = 0.5$. The two-phase separation due to Li^+ -ion order enhances a surface disproportionation reaction $2\text{Mn(III)} = \text{Mn(II)} + \text{Mn(IV)}$ that is followed by Mn(II) dissolution into the electrolyte. The Mn(II) crosses over to the anode to poison Li^+ -ion mobility across the anode SEI layer. As a result, operation on the 4.0-V plateau is plagued by a reduction in capacity that increases with cycling. The Mn(II) dissolution represents a chemical reaction of the electrode with the electrolyte that is to be distinguished from oxidation of the electrolyte by an E_{FC} below the electrolyte HOMO. The progressive increase with cycling in the irreversible loss of capacity is referred to as a capacity fade; it limits the cycle life of the cell. Substitution of Ni or Al and some Li for Mn suppresses any Jahn–Teller framework distortion near $x = 1$; it also disorders the Li^+ ions at $x = 0.5$ to reduce further the Mn(III)-ion concentration at the surface and hence the Mn(II) dissolution, but at the expense of the capacity of the cathode. Figure 17a shows charge/discharge curves for a $\text{Li}_{1-x}[\text{Al}_{0.1}\text{Li}_{0.1}\text{Mn}_{1.8}]\text{O}_4/\text{Li}_{1+x}[\text{Li}_{1/3}\text{Ti}_{5/3}]\text{O}_4$ cell that can undergo safely a fast recharge. At 55°C, this cell retains 80% of its rechargeable capacity after 3,600 cycles. Batteries of five cells connected in series deliver a nominal 12 V.

In the layered $\text{Li}_{1-x}\text{Co}_{0.15}\text{Ni}_{0.85}\text{O}_2$ system, pinning of E_{FC} at the top of the O-2p bands gave an intrinsic limit of 3.8 V versus Lithium for the Ni(IV)/Ni(III) couple. Removal of nearly all the Li from the layered oxide $\text{LiNi}_{0.5}\text{Mn}_{0.5}\text{O}_2$ containing Mn(IV) ions shows not only that Mn(IV) increases the voltage limit of the Ni(IV)/Ni(III) couple by lowering the top of the O-2p bands, but also that where E_{FC} is pinned, oxidation of



Battery Components, Active Materials for. Figure 17

Charge/discharge $V(x)$ versus Li^+/Li^0 for (a) $\text{Li}_{1-x}[\text{Al}_{0.1}\text{Li}_{0.1}\text{Mn}_{1.8}]\text{O}_4$ and (b) $\text{Li}_{1-x}[\text{Ni}_{0.5}\text{Mn}_{1.5}]\text{O}_4$ with $\text{Li}_{1+x}[\text{Li}_{1/3}\text{Ti}_{5/3}]\text{O}_4$ to give terminal single-cell voltages (By courtesy of Prof. T. Ohzuku)

Ni(II) to Ni(IV) occurs without a step in the voltage profile. Moreover, pinning of E_{FC} gives the flat voltage profile of Fig. 17b; at room temperature, Li is removed over the range $0 < x < 1$ at $V \approx 4.7$ V, which is just below the carbonate-electrolyte decomposition voltage above 4.9 V versus Lithium. Batteries with only four

$\text{Li}_{1-x}[\text{Ni}_{0.5}\text{Mn}_{1.5}]\text{O}_4/\text{Li}_{1+x}[\text{Li}_{1/3}\text{Ti}_{5/3}]\text{O}_4$ cells connected in series can deliver a nominal 12 V. Lowering the top of the O-2p bands in the spinel structure increases the intrinsic voltage limit of the oxide. In contrast, the Ti(IV) ion of $\text{Li}_{1-x}[\text{Ni}_{0.5}\text{Mn}_{1.5}]\text{O}_4$ prevents access to even the Ni(III) oxidation state. Unfortunately, although

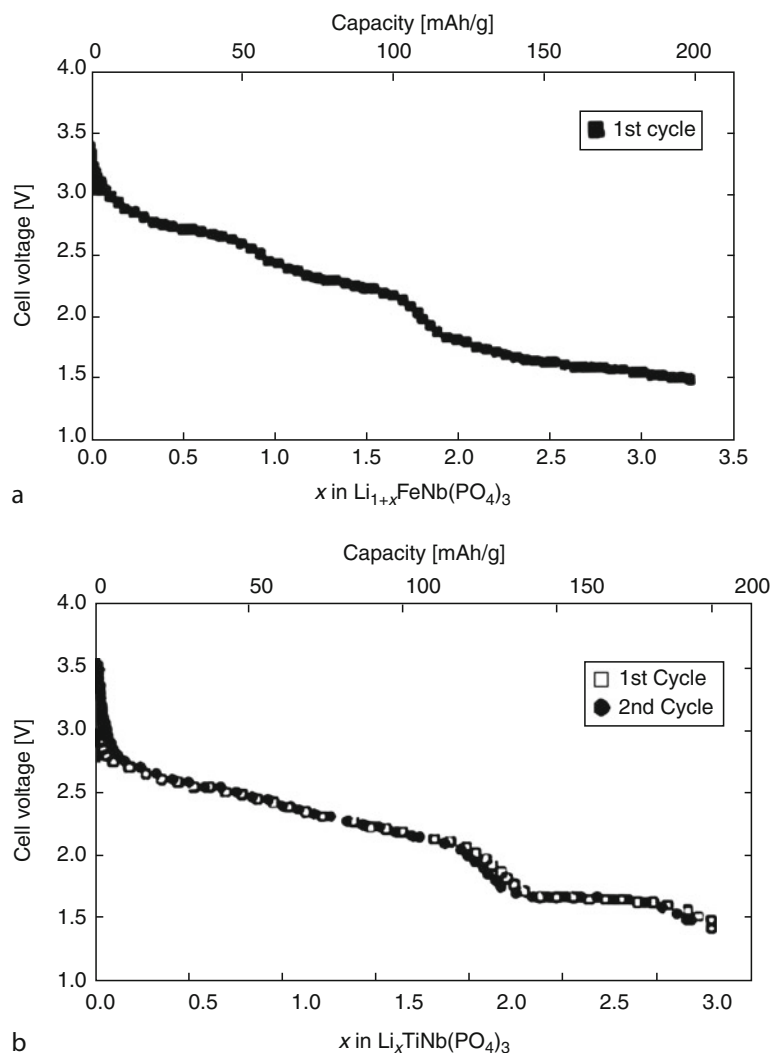
the SEI layer on $\text{Li}[\text{Ni}_{0.5}\text{Mn}_{1.5}]\text{O}_4$ appears to stabilize the cathode at room temperature, raising the temperature to 60°C can introduce a capacity fade on cycling. Coating of the surface of the active oxide particles with another oxide permeable to Li^+ ions has been shown to reduce the activation energy for Li^+ -ion transfer across the SEI layer as well as the capacity fade at 60°C . The spinel $\text{Li}_{0.5-x}[\text{Ni}_{0.5-x}\text{Cr}_{2x}\text{Mn}_{1.5-x}]\text{O}_4$ ($x \cong 0.05$) appears to stabilize the cathode at 60°C without sacrifice of the capacity since the $\text{Cr(IV)}/\text{Cr(III)}$ couple is accessible and small Cr concentration inhibit the disproportionation of Cr(IV) into Cr(VI) and Cr(III) and are sufficient to remove Ni from the particle surface. The development of 12 V batteries based on spinel insertion compounds is targeted for plug-in hybrid vehicles and electrical-energy storage in solar-powered homes. The goal is a life in excess of 10 years and a driving range per charge in excess of 200 miles at an acceptable dollar and environmental cost.

NASICON Framework [20]. Use of a solid Na^+ -ion electrolyte in the Na-S battery stimulated a search in the early 1970s for an improved Na^+ -ion conductor. This search concentrated on open framework structures that were electronic insulators and hosts to mobile Na^+ ions. One of these framework structures was that of the system $\text{Na}_{1+3x}\text{Zr}_2(\text{P}_{1-x}\text{Si}_x\text{O}_4)_3$ with $0 \leq x \leq 1$ having the structure of hexagonal $\text{Fe}_2(\text{SO}_4)_3$ pictured in Fig. 8. This system with $x \approx 2/3$ was named NASICON to signify it is a NA SuperIONic CONductor, and the host framework is now referred to in the literature as the NASICON framework. Substitution of Na^+ ions by Li^+ ions and substitution of a smaller Ti(IV) for Zr(IV) gives LISICON having the same framework; up to 5 Li^+ ions per formula unit can be accommodated in this framework. Substitution of tetrahedral polyatom anions for oxygen opens up the interstitial space for fast Li^+ -ion motion, and substitution for Zr of a smaller transition-metal atom having a lower-energy redox couple makes this framework a candidate host for the cathode of a Li^+ -ion secondary battery. In this host, the octahedral-site cations share corners with the polyatom tetrahedral anions and *vice versa*, which isolates the transition-metal cations from one another. Therefore, the $3d$ configurations at the transition-metal ions are localized, so the successive redox couples are separated from one another by a finite energy gap. This gap may be large, as in the

separation of the $\text{Cr(IV)}/\text{Cr(III)}$ and $\text{Cr(III)}/\text{Cr(II)}$ couples pictured in Fig. 12b or it may be small as between $\text{V(V)}/\text{V(IV)}$ and $\text{V(IV)}/\text{V(III)}$ couples in $\text{Li}_{3-x}\text{V}_2(\text{PO}_4)_3$, vide infra. Since this framework can accommodate up to 5 Li atoms without influencing significantly the redox energies on the octahedral-site cations, the framework lends itself to an examination not only of the influence on the redox energies of the counter cation within the polyatom anion, but also the relative energies of different redox couples for a fixed tetrahedral anion [21].

The $\text{Fe(III)}/\text{Fe(II)}$ redox energy of $\text{Fe}_2(\text{SO}_4)_3$ is at 3.6 eV, those of isostructural $\text{Fe}_2(\text{MoO}_4)_3$ and $\text{Fe}_2(\text{WO}_4)_3$ are at 3.0 eV below the E_{FA} of Lithium. This finding demonstrates that the stronger the covalent bonding in the polyatom anion, the weaker is the bonding of the oxygen to the octahedral-site cation and therefore the more stable is the transition-metal redox energy. This electrochemical result provides a direct measure of the magnitude of this *inductive effect* [22]. It shows that a redox energy can be tuned not only by the position of the guest ion in the interstitial space of the spinel $\text{Li}_x[\text{Mn}_2]\text{O}_4$ or the redox energy of a near-neighbor cation coexisting in an equivalent lattice site as in $\text{Li}(\text{Ni}_{0.5}\text{Mn}_{0.5})\text{O}_2$ versus $\text{Li}(\text{Ni}_{0.8}\text{Co}_{0.2})\text{O}_2$, but also by the counter cation in a polyatom anion. Accordingly, the $\text{Fe(III)}/\text{Fe(II)}$ redox couple in $\text{Li}_{3+x}\text{Fe}_2(\text{PO}_4)_3$ is 2.8 eV below the E_{FA} of Lithium. The 0.8 eV shift of the $\text{Fe(III)}/\text{Fe(II)}$ redox couple on changing from $(\text{SO}_4)^{2-}$ to $(\text{PO}_4)^{3-}$ is the same for all the redox energies of the NASICON framework.

As an illustration of how the structure lends itself to locating the relative positions of the available redox energies, Fig. 18a shows the voltage profile for $\text{Li}_{1+x}\text{FeNb}(\text{PO}_4)_3$ showing discrete steps on passing from the $\text{Fe(III)}/\text{Fe(II)}$ to the $\text{Nb(V)}/\text{Nb(IV)}$ couple to the $\text{Nb(IV)}/\text{Nb(III)}$ couple at 2.8 eV, 2.3 eV, and 1.8 eV, respectively, below the E_{FA} of Lithium. The $\text{Ti(IV)}/\text{Ti(III)}$ couple at 2.5 eV in $\text{Li}_x\text{TiNb}(\text{PO}_4)_3$ overlaps the $\text{Nb(V)}/\text{Nb(IV)}$ couple at 2.5 eV to give the smooth voltage profile from 2.5 to 2.2 V shown in Fig. 18b. The relative energies of the redox couples with $(\text{SO}_4)^{2-}$ anions remain the same, but all are shifted by about 0.8 eV to lower energy. The voltage profile of a carbon-coated $\text{Li}_{3-x}\text{V}_2(\text{PO}_4)_3$ cathode versus Lithium shows a good cycle life over the interval $0 \leq x \leq 3$ with two-phase reactions at 3.59 V in the interval $0.5 \leq x \leq 1.0$

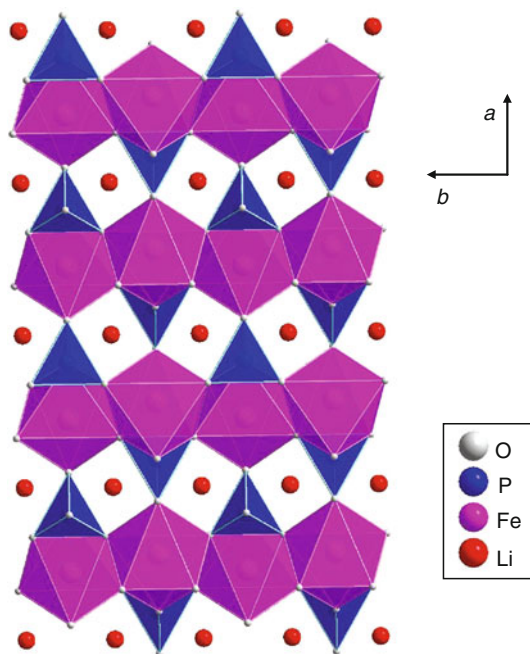


Battery Components, Active Materials for. Figure 18

Discharge $V(x)$ versus Li^+/Li^0 for (a) $\text{Li}_{1+x}\text{FeNb}(\text{PO}_4)_3$ and (b) $\text{Li}_x\text{TiNb}(\text{PO}_4)_3$

and 3.67 in the interval $1.0 \leq x \leq 2.0$ corresponding to the V(IV)/V(III) couple and 4.06 V over $2.0 \leq x \leq 3.0$ of the V(V)/V(IV) couple. The 0.08 eV step for the V(IV)/V(III) couple is due to ordering of the Li^+ ions into the unique interstitial site per formula unit between M-atom sites of the framework; the larger 0.4 eV step at $x = 2.0$ is the separation of the V(IV)/V(III) and V(V)/V(IV) couples. Carbon coating of the particles is needed to facilitate these two-phase reactions; the large separation of the transition-metal ions makes any electron transport diffusive, which limits the power capability with this framework unless small, carbon-coated particles are used.

Ordered Olivines LiMPO_4 . As in a spinel [23], in the olivine structure of Mg_2SiO_4 , the cations occupy half of the octahedral and one-eighth of the tetrahedral sites of a slightly distorted, close-packed anion array, but the olivine anion array is close-packed-hexagonal rather than close-packed-cubic. Moreover, two types of occupied octahedral sites are distinguishable, which leads to an ordering of Li^+ and M(II) ions in the LiMPO_4 olivines whereas they are disordered in the spinel $\text{V}[\text{LiM}]\text{O}_4$. The ordered MPO_4 array forms a 3D strongly bonded framework in which octahedral-site M atoms share corners within $a-c$ planes of an orthorhombic unit cell, Fig. 19; these $a-c$ planes are

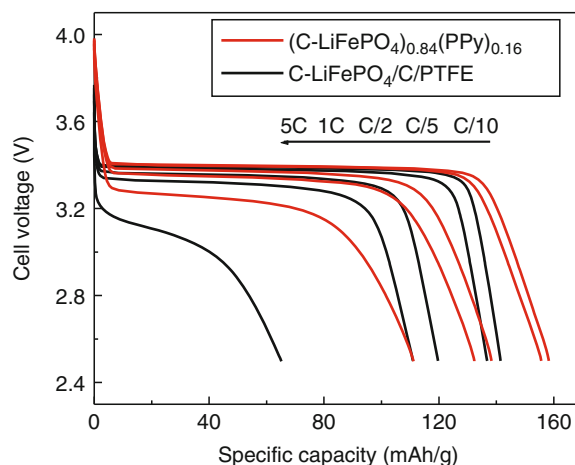


Battery Components, Active Materials for. Figure 19
Structure of the ordered olivine LiFePO_4

bridged by the PO_4 tetrahedra and the guest Li^+ ions occupy 1D a -axis tunnels of edge-shared octahedra. Motion of the Li^+ ions to neighboring empty octahedral sites outside of the tunnels requires a larger activation energy than motion along the tunnels.

The M atoms of LiMPO_4 may be Mg, Mn, Fe, Co, Ni, or mixtures thereof. Of these possibilities, LiFePO_4 is the most promising cathode material; $\text{Li}_{1-x}\text{FePO}_4$ provides a flat $V = 3.45$ V versus Lithium. Removal of Li from LiMnPO_4 is difficult, but the Mn(III)/Mn(II) couple gives a more attractive $V = 4.1$ V. The Co(III)/Co(II) couple near 4.8 eV below the E_{FA} of Lithium is at the limit where a liquid-carbonate electrolyte becomes unstable.

It is not possible to substitute an aliovalent cation for Fe(II) in LiFePO_4 . Synthesis of LiFePO_4 from nonstoichiometric starting mixtures results in the dissolution of a separate phase to the surface of stoichiometric LiFePO_4 particles. Electrochemical removal of Li results in the formation of FePO_4 as a separate phase. This situation means that the electronic conductivity remains low and the voltage profile of $\text{Li}_{1-x}\text{FePO}_4$ is flat. In order for Li^+ ions to move in or out of a particle rapidly with the electron of an Fe(III)/Fe(II) couple, it



Battery Components, Active Materials for. Figure 20
Discharge $V(x)$ versus Li^+/Li^0 for C-coated Li_xFePO_4 with/without PPy for different rates for full discharge from C/10 = 10 h to 5 C = 12 min

is necessary to have an electronically conducting coat on a small nanosize particle that also not only makes electronic contact with the current collector, but also is permeable to Li^+ ions. This coat may be a phase rich in Li that is dissolved from the LiFePO_4 particle or carbon; the coat makes electronic contact with the current collector either by added inert carbon or by contact to an electronically conducting polymer that also contacts the current collector and has an active redox energy that overlaps the energy of the Fe(III)/Fe(II) couple of LiFePO_4 . Polypyrrole (PPy) and polyanniline (PANI) are two such polymers [24]. Figure 20 illustrates the voltage profile versus Lithium of carbon-coated LiFePO_4 with PPy for different charge/discharge rates. With a $V = 3.45$ V well below the 4.3 V limit imposed by the HOMO of the electrolyte, this cathode is safe; it also has an excellent cycle life. This cathode is used in secondary Li^+ -ion power batteries and is an attractive contender for the battery of a plug-in hybrid vehicle despite a redox energy that is 1 eV higher than would appear to be optimal for a carbonate electrolyte.

It should be noted that LiFePO_4 nanoparticles embedded in a carbon matrix make a composite that shows promise for the cathode of an electrochemical capacitor of higher energy density than a purely carbon cathode.

Secondary Batteries with Cathodes That Are Not Insertion Compounds

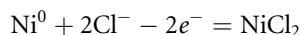
The cell of a *sodium–sulfur* battery, illustrated schematically in Fig. 21, consists of two liquid electrodes, molten sodium and sulfur, separated by a ceramic Na^+ -ion electrolyte; it operates in the 300–375°C range to maintain molten not only the sodium anode, but also both the sulfur cathode and the immiscible-in-sulfur sodium polysulfide (Na_2S_5 to Na_2S_3) products of the reaction of Na^+ ions from the electrolyte with the sulfur [2]. Because sulfur is an electronic insulator, the reaction of the Na^+ ions with the sulfur occurs at the surface of a carbon felt introduced into the sulfur to bring electrons to a large carbon–sulfur interface area. The negative post of the battery is attached directly to the molten sodium contained in a ceramic-electrolyte tube that is closed at one end and open to a molten-sodium reservoir at the other end; the reservoir keeps the Na^+ -ion electrolyte covered with Na throughout a discharge. The sulfur with its carbon felt bathes the outside of the ceramic-electrolyte tube, the carbon felt contacting a metal container to which the positive post is attached. The critical component of the cell is the Na^+ -ion ceramic electrolyte.

The Na^+ -ion electrolyte for a Na–S battery needs to consist of a framework host with mobile Na^+ ions in the

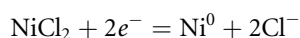
interstitial space, but it must also have the bottom of the conduction band of the host above the E_{FA} of elemental Sodium. These criteria are met in the Na- β and Na- β'' aluminas; but their frameworks have a 2D interstitial space and, therefore, an anisotropic thermal expansion. This anisotropic property is undesirable for a polycrystalline, thin ceramic membrane that is subject to repeated thermal cycling between room temperature and 350°C. Nevertheless, ceramic engineering of mixed β and β'' aluminas has resulted in a viable Na–S battery for stationary electrical-energy storage [25].

Stoichiometric Na- β alumina, $\text{Na}_2\text{O} \cdot 11\text{Al}_2\text{O}_3$, contains $\text{Al}_{11}\text{O}_{16}$ spinel slabs perpendicular to the [111] axis; the slabs are connected by oxygen bridges within intervening NaO planes containing intersecting 1D tunnels occupied by the Na^+ ions. In stoichiometric Na- β alumina, there are two inequivalent Na^+ -ion sites in the NaO planes, one of which is occupied and the other empty. The inequivalence of the Na^+ -ion sites raises the activation energy ΔH_m for Na^+ -ion motion, but the introduction of excess Na^+ either in $(1+x)\text{Na}_2\text{O} \cdot 11\text{Al}_2\text{O}_3$ or by substituting some Li^+ or Mg^{2+} for Al^{3+} in the spinel blocks reduces ΔH_m in the β phase; in the β'' phase, the Li^+ or Mg^{2+} substitutions shift the spinel slabs relative to one another to make equivalent the Na^+ -ion sites in the NaO layers, thereby reducing ΔH_m . A two-phase mixture of β and β'' phases with excess Na^+ ions gives a viable ceramic membrane.

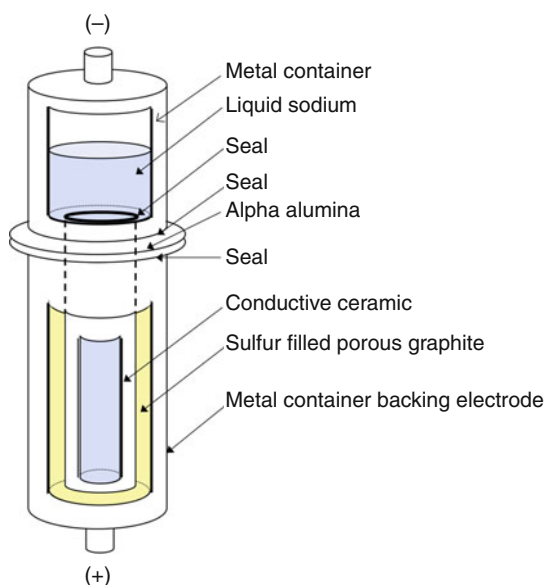
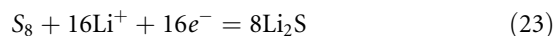
The ZEBRA cell, which is under development by the General Electric Co., uses a molten-sodium anode and a solid β, β'' -alumina solid electrolyte as in the sodium–sulfur cell, but the positive electrode is large-surface-area nickel rather than molten sulfur with a large-surface-area current collector. The electrolyte on the cathode side of the ZEBRA solid electrolyte is an aqueous NaAlCl_4 containing NaCl and NaI as well as a little FeS. The FeS and NaI are added to limit growth of the Ni particles and to aid the overall cathode reaction, which is



on charge and on discharge



at a $V_{\text{OC}} = 2.58$ V. A *Lithium–Sulfur* battery also uses a sulfur cathode; its redox reaction is



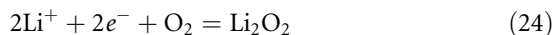
Battery Components, Active Materials for. Figure 21
Schematic of a sodium–sulfur cell

in which the electrons from the anode on discharge are brought to the reaction by carbon [26]. The two-phase reaction proceeds in two steps, first to the polysulfides Li_2S_8 , Li_2S_4 , and Li_2S_2 at 2.4 V and then to Li_2S at 2.0 V. Best results to date have been obtained with a CMK-3 carbon impregnated by sulfur and electrolyte. The CMK-3 carbon consists of carbon nanorods kept apart by carbon bridges to give channels into which molten sulfur is introduced. On solidification, channels are opened for the impregnation of electrolyte to give Li^+ ions access to a large surface area of amorphous sulfur. The cathode reaction is relatively slow, and the efficiency of electrical-energy storage is not optimal. Nevertheless, the lower power density and the low voltage are compensated by a capacity of over 1,000 mAh/g. The low voltage requires use of a Li^0 anode. A protected Lithium anode (see Lithium/seawater battery) is a logical candidate for this battery, but a soluble Li_2S_n shuttle molecule may suppress build-up of the dendrites on the Li^0 anode. The jury is still out on whether this battery will be competitive for a low-power application.

Lithium–Metal Salt secondary batteries are analogous to the Lithium–seawater primary battery [3]. A Li^+ -ion solid electrolyte separates a nonaqueous anolyte and an aqueous cathode. For example, a Lithium anode with a carbonate anolyte and an aqueous $\text{Fe}(\text{CN})_6^{3-}/\text{Fe}(\text{CN})_6^{4-}$ cathode has been shown to give a flat voltage $V \approx 3.4$ V with an efficiency that increases with the molar ratio of iron cyanide in the cathode solution [27]. This promising approach requires development of a Li-ion solid electrolyte having a $\sigma_{\text{Li}} > 10^{-4}$ S/cm at room temperature that is stable to an acidic cathode solution and is not reduced by contact with a Li^0 dendrite on the anode side.

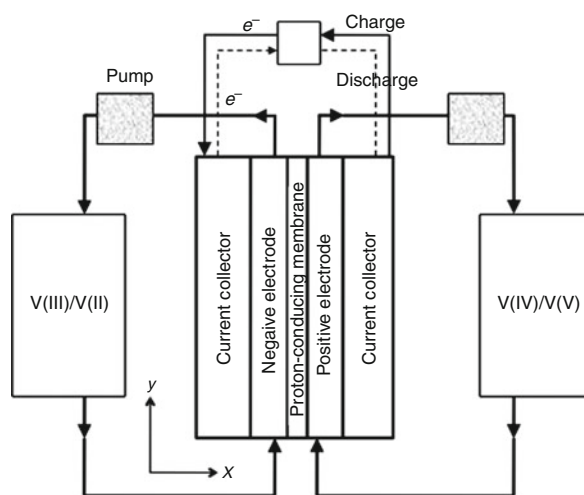
Lithium–air batteries [28] may also use a solid separator that will block dendrite growth from the anode to the cathode but allows permeation of the Li^+ ion between an anolyte and a catholyte. The simplest such separator would be a solid Li^+ -ion solid electrolyte, but a porous glass containing the liquid electrolyte has been used where the anolyte and the catholyte are identical. As in the Zn–air primary battery, a porous carbon containing an oxygen–reduction catalyst on the pore walls and the liquid electrolyte in the pores provides the structure needed to facilitate the catalytic reaction of

Li^+ ions with the gaseous O_2 cathode. The cathodic reaction



is reversible, but the voltage difference between charge and discharge currents is large even with the best catalyst, Pt–Au nanoparticles [29], which makes the battery inefficient for electrical-energy storage.

The **Redox-Flow Battery** [30] is a candidate for medium- and large-scale electrical-energy stationary storage. The cells of these batteries contain different redox energies in a liquid anode and a liquid cathode separated by either a solid electrolyte or a microporous polymer or glass separator. Reversible electrode processes take place at the surface of graphite-felt current collectors as in the sulfur cathode of a Na–S cell. The reactant redox couples flow across the carbon-felt conductors, entering the electrochemical cell from external reservoirs, Fig. 22. In theory, the capacity of a cell is determined by the volumes of the two electrolyte tanks. Under development is a cell containing vanadium ions in sulfuric-acid solution. The anode compartment contains V^{2+} ions, the cathode compartment VO_2^+ ; the cell reactions are



Battery Components, Active Materials for. Figure 22
Schematic of the all-vanadium flow-through battery

to take advantage of the 1.65 eV difference between the V(III)/V(II) and V(V)/V(IV) redox couples. Alternative couples include, for example, $\text{Fe}^{3+}/\text{Fe}^{2+}$ and $\text{Cr}^{3+}/\text{Cr}^{2+}$. These cells can achieve 80–90% energy-storage efficiencies in large installations at a low cost per kWh. They promise a long cycle life, are relatively easy to maintain, and can be fully cycled without harm to the battery. However, in order to realize the commercial potential of these batteries, several challenges must be met, including development of electrodes resistant to oxidation in its electrolyte, membrane stability and prevention of redox crossover through the separator membrane while maintaining a fast H^+ -ion transport across the membrane, easier flow across the current collectors, and scale-up optimization.

Future Directions

The Li-ion battery has already introduced the wireless revolution by powering the cell telephone and the laptop computer as well as their derivatives. Modest increases in anode capacity will improve the volume energy density for handheld electronic devices.

The Li-ion battery is also powering portable electric-power tools and small electric vehicles. However, its widespread application to the plug-in hybrid electric vehicle and the all-electric vehicle will depend on lowering the cost while increasing the driving range between recharges. To reach this target, it will be necessary to develop new cathode strategies. These strategies appear to depend on the development of a suitable solid electrolyte and sealants that can prevent crossover of different liquid electrolytes either side of the solid electrolyte.

Electrical-energy storage in batteries for the grid for increasing the efficiency of nuclear energy and for enabling the large-scale introduction of wind and solar energy will probably need the much larger capacities offered by flow-through batteries. In the interim, rebirth of the Na/S battery may provide some large-scale electrical-energy storage.

Realization of the great societal benefits to be derived from the new battery technologies has galvanized an extensive research activity that promises continued development.

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Electrical Modeling for Batteries
Lead Acid Batteries
Nickel-Cadmium Battery
Nickel Metal Hydride Batteries
Lithium-Ion Batteries
Metal–Air Batteries
Zinc Bromine Battery
Supercapacitors
Recommendations for Future Work
Bibliography

Definition of the Subject

The demand for high performance and long life storage systems has lead to numerous research initiatives, aimed at the development of such systems. Developmental paths are aligned with the requirements of the applications of these systems. A detailed understanding of technical characteristics and cost considerations is provided in this paper for various battery chemistries: contemporary, vintage, and prospective. A clear understanding of battery characteristics is essential for guiding the selection of such batteries. Indeed, because of the critical functions fulfilled by batteries as well as the substantial costs of advanced batteries, a realistic appraisal of candidate battery performance and costs against requirements is key to judging the prospects of new applications such as EV, HEV, and plug-in hybrid electric vehicles (PHEV). Although electric vehicles (EVs) have been around since before 1900 the limitations of the batteries to drive them have not enabled them to compete in the general consumer's market with the internal combustion engine. Automotive parts are limited by space and weight. Therefore EVs and hybrid electric vehicles (HEVs) require a battery with high energy density. Specific energy is defined as the energy per kilogram of the battery while energy density is the energy per unit volume. Early designs (1990–1995) of lithium-ion batteries only had a specific energy of 0.2 kWh/kg. EVs also require a battery with high power output for large power draw, such as quick acceleration. The General Motors EV1 had a battery pack weighing almost 600 kg while the car weighed 1,350 kg. The battery would then account for more than 44% of the car's weight. A marked improvement in energy cell density of batteries was required for practical EVs.

Battery Technologies

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Article Outline

Definition of the Subject

Introduction

Basic Characteristics of Batteries

Introduction

In this paper, the first section covers the relationship between the internal resistance of the cell, maximum power output, energy efficiency in charging and discharging, and reduction of cell heating. This is followed by a review of the characteristics of lead acid, nickel metal hydride, lithium-ion batteries, and supercapacitors.

Recent advances in power electronics provide competitive performance for electric cars so they provide the necessary acceleration for wide spread adoption [1]. However batteries still lack the energy density of gasoline or diesel fuels and thus cannot compete in terms of the overall range that can be driven between recharging. Additionally, recharging may be slow. However, ongoing research and improvements in manufacturing may reduce both energy density limitations and costs. Concerns about greenhouse gases and other air pollutants are the other driving factors for the renewed interest in EVs and HEVs, which may reduce or eliminate the emission of NO_x , CO_2 , and hydrocarbon pollution from mobile vehicles depending on how the electricity used to charge the battery was generated. EVs and HEVs also reduce noise levels when running on electric mode. In 2009, 1.6 million HEVs were registered in the USA [2].

This section concentrates on a variety of battery technologies that have shown significant promise for long life and high performance. A brief, generic list of battery characteristics are provided in section “[Electrical Modeling for Batteries](#)”. Section “[Lead Acid Batteries](#)” introduces various types of lead acid battery chemistries. Section “[Nickel Metal Hydride Battery](#)” introduces the nickel metal hydride chemistry, while lithium-ion is discussed in section “[Lithium-Ion Batteries](#)”. The upcoming technology of supercapacitors is also introduced and a comparison to conventional electrochemical counterparts is provided.

This entry first gives a general overview of characteristics of batteries, followed by the electrical modeling used for batteries in EVs and concludes by presenting the different battery technologies used today.

Basic Characteristics of Batteries

An electrical battery is a power source composed of one or more electrochemical cells which convert stored chemical energy into electrical energy. In this section,

rechargeable batteries which can be used multiple times is discussed. A battery is composed of one or more electrochemical cells, each consisting of two electrodes and one (or two) electrolyte-containing anions and cations.

Figure 1 depicts the typical electrochemical cell voltage behavior during charging (labeled “Charge curve V”) and discharging (labeled “Discharge curve V”). Cell voltage drops and rises during discharging and charging respectively, in proportion to the cell’s internal voltage. The difference between the terminal open-circuit voltage and the discharge and charge voltage is attributed to the cell’s internal resistance. An ideal cell provides constant terminal voltage until empty. The internal resistance of real cells prevent ideal performance during discharge resulting in lower terminal voltage.

The essential characteristics of batteries are maximum power output, charging/discharging efficiency, and temperature effects. These are key factors to be considered when designing or choosing batteries for particular applications. These characteristics are further elaborated for each battery in the device specific sections of the paper. The basic definitions are shown below.

Maximum power output: A lower limit is set for each cell’s voltage. The maximum dischargeable current value is determined such that the cell voltage does not fall to this limit. The maximum current is determined as

$$I_{\max} = (\text{Open Circuit Voltage} - \text{Lower Limit Voltage}) / \text{Internal Resistance}$$

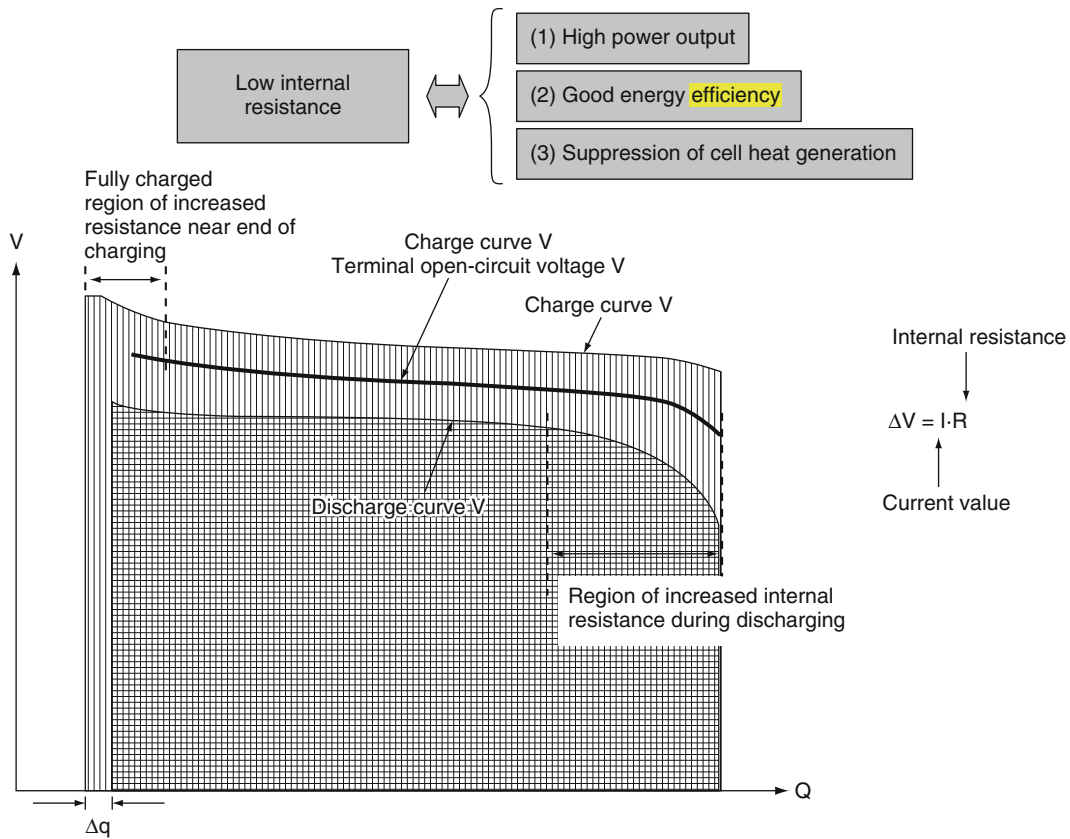
Then, maximum power output of a cell can be calculated as $P_{\max} = I_{\max} \bullet (\text{Open Circuit} - \text{Lower Limit Voltage})$. High power output requires low internal cell resistance.

Charging/discharging efficiency: Electrical energy transferred during a charging/discharging cycle can be computed as

$$E = \Delta Q \bullet V$$

where ΔQ is the transferred charge and V is the terminal voltage at that time.

In Fig. 1, the *area* between the charge curve and the horizontal axis is the total electrical energy transferred to the battery. Accordingly, the area between the discharge curve and horizontal curve is the total energy



Battery Technologies. Figure 1

Cell voltage profile and internal resistance in charging and discharging operations with respect to cell charge Q [3]

drained from the battery. Battery efficiency is a ratio of discharge to charge energy values. It is imperative to reduce the difference between these two curves to improve battery efficiency.

Temperature effect: Charging and discharging cycles can cause a cell's temperature to rise. For lithium-ion cells, operating temperatures above 50°C can lead to cell degradation. Ozawa [4] attributes the difference in charging and discharging curves in Fig. 1 to heat lost due to different operating temperatures. To suppress this difference, the cell's internal resistance must be reduced.

Electrical Modeling for Batteries

A simple model of a battery can help alleviate issues of understanding of a battery's behavior. The simplest electrical equivalent model of a cell is a voltage source with a resistor in series, as shown in Fig. 2a. This is the

internal resistance of the cell. Davide [5] provides corresponding voltage and current response curves for each proposed model.

A more complex model is described in Fig. 2b. This model emulates the behavior of a battery when instantaneously loaded. The initial voltage drop across battery terminals is small, due to R_1 . The voltage then drops exponentially to the level of both resistances with a time constant $T = R_2 \cdot C_2$ (~ 1 min). This phenomenon is known as relaxation.

A variation on 2b is 2c, where the time constant $T = R_3 \cdot C_3$ is ~ 1 ms. This model correctly emulates AC impedances on the order of 1 kHz. This property can however be misleading to the user since such impedances are usually measured with no load by the manufacturer. The user may also misread this impedance as the cell's DC resistance. Figure 2(d) combines 2(b) and 2(c) and thus equally satisfies both the manufacturer and the user.

Internal resistance of a cell results from a series combination of resistances due to bulk metal, chemical processes, and terminals. Varying loads can have dynamic effects on these properties of a battery. Thus the battery’s internal resistance (R_i) also has dynamic properties. Davide explains that internal resistance can vary with the following battery characteristics:

State of charge:	R_i is high for both high and low state of charge levels
Temperature:	R_i is higher at cold temperatures
Current:	R_i is higher at higher currents when charging (compared to the same current when discharging)
Usage:	R_i increases over time with cell usage

Figure 3 shows how the internal resistance of a lithium iron phosphate (LiFePO_4) battery varies versus the above four battery characteristics.

For preliminary research purposes, it is entirely possible to create a generic model and vary key parameters to simulate the performance of various battery chemistries. Table 1 provides a list of key parameters for

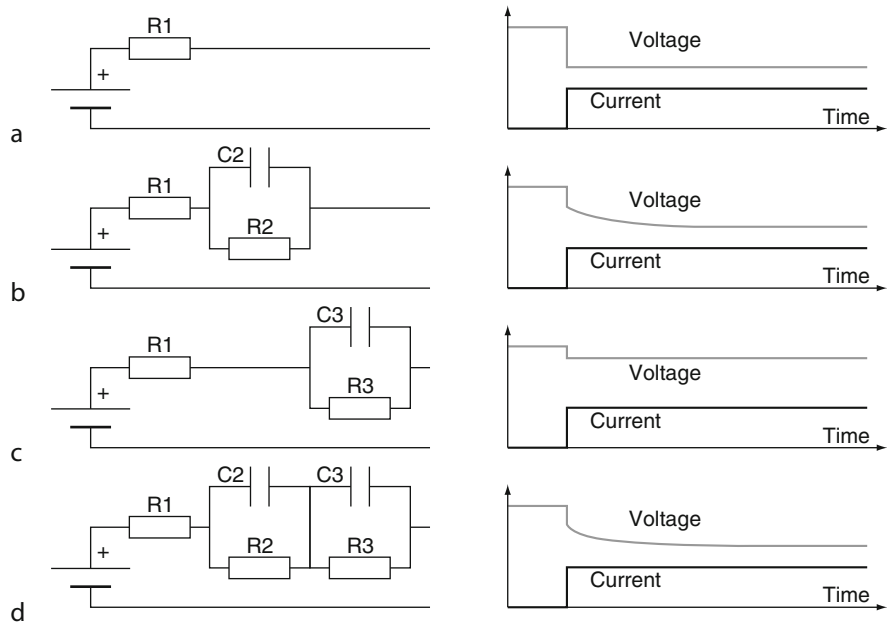
three batteries chemistry as well as three types of supercapacitors.

Detailed reviews of various battery chemistry compositions are provided in the following sections. We consider not only relevant chemical reactions, but also applications, cost, and efficiency concerns associated with every chemistry type. The following section details lead acid batteries, their cell construction, and the electrochemistry, for several types of lead acid batteries used in EVs and their characteristics.

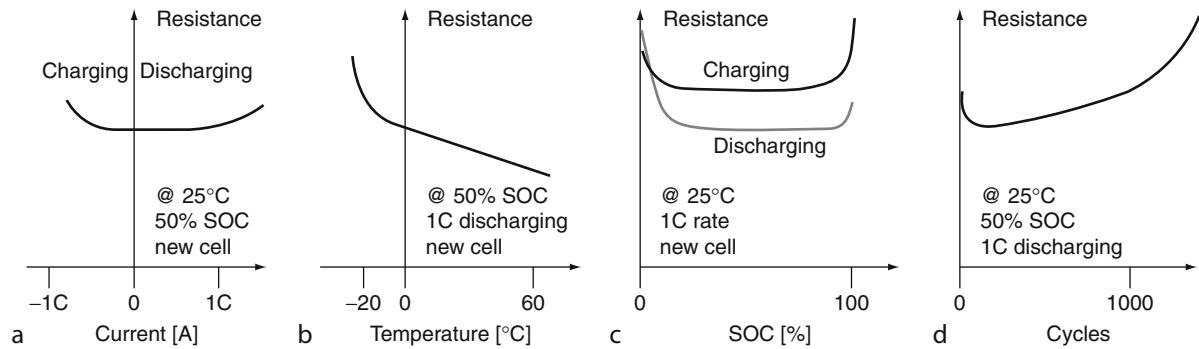
Lead Acid Batteries

Lead acid (PbA) batteries are inexpensive and have characteristics somewhat suitable for energy storage in EVs. Design is possible for short, high-rate discharges or for bulk energy storage. These batteries are commonly used to power the starter motor of conventional internal combustion engines.

Lead acid batteries are classified into two broad categories, traditional vented lead acid (VLA) batteries and valve-regulated lead acid (VRLA) batteries. The latter have dominated the stationary battery market over the past 20 years [1]. VRLA batteries have immobilized electrolyte and a means to recombine



Battery Technologies. Figure 2
Electrical modeling schemes for a battery [5]



Battery Technologies. Figure 3
Internal resistance variation for a LiFePO₄ battery [5]

Battery Technologies. Table 1 Performance parameters

	Lead acid	Nickel metal hydride	Lithium-ion	Super capacitors		
Electrolyte	H ₂ SO ₄ + H ₂ O	KOH	LiPF ₆	Aqueous electrolyte	Organic electrolyte	Aqueous electrolyte
Anode	PbO ₂	M (Metal)	Graphite	Carbon	Carbon	Metallic
Cathode	Pb	Ni(OH) ₂	LiMn ₂ O ₄	Carbon	Carbon	Metallic
Cell voltage (V)	2.4	1.2	4.0	1	3	1
Specific energy (Wh/kg)	35	50–80	250–400	0.2–1.3	3–6	1
Relaxation time constant (s)	5	2	1	N/A	N/A	N/A
AC impedance time constant (s)	10 ⁻¹ –10 ⁻³	10 ⁻¹ –10 ⁻³	10 ⁻³	N/A	N/A	N/A
Recommended operating temperature (°C)	25	–20 to 50	50	–25 to 85	–40 to 85	–30 to 70

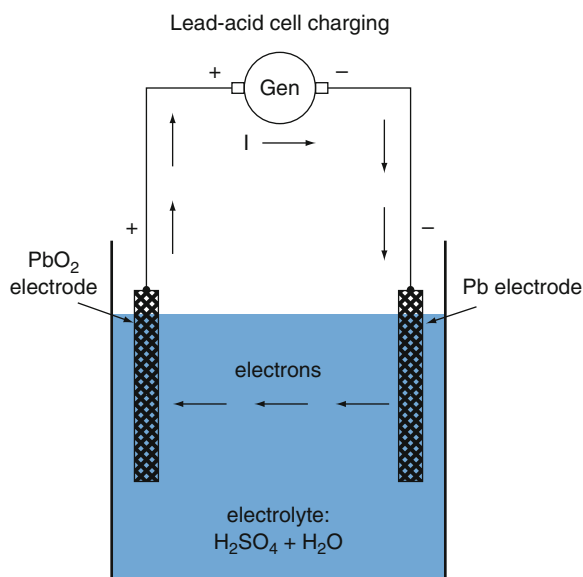
charged gas, thus conserving water in the cell. They are typically smaller than their vented counterparts and require less maintenance. Most of the VLA and VRLA batteries use pasted plate construction, in which a mixture of active materials is pasted onto lead alloy grids. The characteristics of the final battery are heavily influenced by the alloy composition. Tubular plate construction is also quite common, in which the active material is held in non-woven fibrous tubes with a center conductor of lead alloy.

Lead acid batteries have less energy density and specific energy as compared to the more recent lithium-ion and NiMH batteries but these batteries generally have high ampere rating. Since lead acid batteries

do not have the deep cycling capability and energy density compared to other batteries used in EVs, they are being replaced by NiMH and Li-ion batteries for traction purposes. However earlier EVs used lead acid batteries like the GM EV1 (Generation 1). The Delphi 704 VRLA-Prismatic battery has an ampere rating of 53 Ah and a specific energy of 35.3 Wh/kg. These batteries have a good cycle life of 15,000–30,000 cycles. In the following section, the cell construction and electrochemistry of lead acid batteries are discussed [4].

Cell Construction and Electrochemistry

All lead acid designs share the same basic chemistry. The positive electrode (cathode) is formed of porous lead



Battery Technologies. Figure 4
Charging lead acid cell schematic [3]

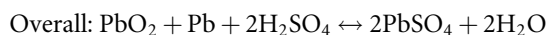
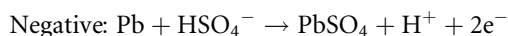
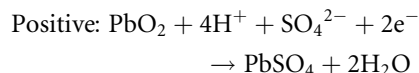
dioxide (PbO_2) while the negative electrode (anode) is composed of sponge lead (Pb). Sulfuric acid (H_2SO_4) in water serves as gelled electrolyte between the two electrodes. Lead dioxide at the cathode is supported by a thin lead grid. Figure 4 provides a cross-sectional view of a standard lead acid battery cell.

Pure lead is generally too soft to be used as a plate material and usually requires addition of an alloy. Alloy candidates vary and are responsible for positive plate subtypes such as lead-antimony, lead calcium, and pure lead. Lead-antimony cells are recommended for applications requiring very long life and discharging to depths greater than 20% of rated capacity. Pure lead cells are recommended for float and shallow cycling service where average discharge depth is less than 20%. Finally, pure lead alloy cell types are used when very low charged stand loss is a requirement in the application and occasional deep cycles are expected [6].

During charging, as the cell approaches full charge, a majority of the PbSO_4 is converted to Pb and PbO_2 . Beyond this point and under high charging voltages, cell voltage becomes greater than the gassing voltage (about 2.39 V per cell) and the overcharge reactions begin. This results in the electrolysis of the water contained in the electrolyte, and the production of hydrogen and oxygen. In sealed lead acid cells, this

reaction is controlled to minimize hydrogen evolution and loss of water by recombining evolved oxygen with the negative plate.

The discharge chemical reactions are as follows:



As the cell discharges, lead at the anode reacts with hydrogen sulfate ions to form lead sulfate, along with hydrogen ions and electrons. These electrons then travel through the external circuit. Note that sulfuric acid is a strong electrolyte and breaks down into hydrogen and hydrogen sulfate ions even before being placed in the battery. This breakdown is independent of the battery plates. At the cathode, lead dioxide is reduced by the two electrons released at the anode and the lead ion then reacts with sulfate to form lead sulfate along with water. Discharge continues until all of the sulfuric acid is converted to water. Discharging is an exothermic process and charging is an endothermic process.

As discharging progresses, the concentration of the sulfuric acid electrolyte falls. As a result, the no-load (open circuit) voltage of a lead acid cell varies during a cycle from approximately 2.1 V at the top of charge to approximately 2 V at the bottom of discharge. In addition, the decreasing concentration of electrolyte leads to an increasing internal resistance that reduces overall efficiency of the cell. All these factors come together to signify for a given current, the terminal voltage of a lead acid cell is lower at the end of discharge than at the beginning [3].

Lead is insoluble and stays at either plate during charging or discharging. This property allows recharging of the battery. In contrast, non-rechargeable batteries contain reaction products that either convert to an insoluble precipitate or are lost as gas.

Two side reactions can occur in lead acid cells, primarily at the top of charge: hydrogen production from the lead negative plates and oxygen generation from the lead dioxide positive plate. In flooded cells, these side reactions lead to a loss of water that must be made up periodically. The loss of water is particularly high during overcharge and equalization of batteries of

cells, which must be performed each full charge and once every 10 or 20 cycles, respectively. Overcharge and equalization both involve charging the lead acid cells somewhat beyond the ampere-hour capacity that has been discharged, so as to ensure that all the electrodes of all the cells of the battery are fully and equally recharged [3].

The next section gives a brief description of the different types of lead acid batteries.

Types of Lead Acid Batteries (by Electrode Material)

Lead Calcium Batteries Lead acid batteries with electrodes that are modified by the addition of calcium are more resistant to corrosion, overcharging, gassing, water usage, and self-discharge. All of these factors shorten the life of a battery. The increased resistance increases the battery life of lead calcium batteries. Additionally, they have a larger electrolyte reserve area above the plates, higher cold cranking ampere ratings, and require little maintenance [4].

Lead-Antimony Batteries Lead acid batteries with electrodes modified by the addition of antimony improve the mechanical strength of electrodes which is important for EV and deep discharge applications. Water loss and the internal heat are also minimized. They have a longer life than lead calcium batteries. These batteries are also easy to recharge when they are completely discharged and are comparatively less expensive compared to other types of lead acid batteries. However, lead-antimony batteries have a higher self-discharge rate typically 2–10% per week, whereas lead calcium batteries have a self-discharge rate of 1–5% per month [4].

Advanced Lead Acid Batteries In the early part of the decade, the lead acid battery community formed the Advanced Lead–Acid Battery Consortium (ALABC) in a concerted effort to make electric vehicles a reality by overcoming the shortcomings of the VRLA battery. Much has been achieved by the global research and development program of the ALABC [7].

The ALABC originally developed advanced lead acid batteries as a replacement for the more expensive NiMH batteries used in hybrid electric vehicles. These advanced lead acid batteries exhibit better performance as compared to VRLA batteries, in terms of stationary

energy storage [8]. Some of the results of research in advanced lead acid batteries are discussed below.

Swelling of the positive active material in the direction normal to the plane of the plate remains a serious concern for VRLA batteries. The tendency for the positive active material to expand with repeated deep cycling is, however, beyond dispute. Experimental work at the University of Brno demonstrated a clear correlation between loss of capacity with cycling and increase of active-material resistance which is presumed to arise as a result of swelling [7].

An in-depth study of positive-grid alloys demonstrated that the introduction of tin brings additional benefits in the form of enhanced corrosion resistance and reduced electronic resistance. Positive grids that contain no antimony but have 1–1.5% by weight of tin do not suffer expansion in the plane of the plate and as a result of the lower corrosion rate, it is possible to contemplate a substantial reduction in grid thickness and weight in order to increase the specific energy [7].

Also, the ALABC development work discovered that adding a small amount of carbon (2–4% by weight) to the negative active material of the electrode minimized negative plate sulfation and enhanced VRLA battery cycling performance in partial-state-of-charge cycling. Battery developers/suppliers who are currently involved in research and development of advanced lead acid batteries include East Penn, North Star, Exide technologies, Axion Power, and Furukawa [8].

Types of Lead Acid Batteries (by Construction)

Flooded/Vented Lead Acid Batteries These batteries have electrodes or plates which are immersed in the electrolyte. The level of the electrolyte reduces as a result of charging and the gases formed which are vented to the atmosphere, so distilled water is added to bring the electrolyte back to its initial level. The most familiar example of a flooded lead acid cell is the 12 V automobile battery.

Valve Regulated Lead Acid (VRLA) Batteries VRLA batteries are also called sealed lead acid (SLA) batteries. They are designed to prevent electrolyte loss through evaporation, spillage, and gassing, which in turn prolongs the life of the battery and reduces maintenance cost. Instead of simple vent caps on the cells to let gas

escape, VRLA batteries have pressure valves that open only under extreme conditions. Hydrogen and oxygen are generated by galvanic action of the battery during charging. VRLA batteries need an electrolyte which reduces gassing by impeding the release of these gases to the atmosphere. A catalyst is usually involved that causes the hydrogen and oxygen to recombine into water. This system is called a recombinant system. Since acid electrolyte spillage is eliminated, these batteries are safer [4]. There are two categories of VRLA batteries.

Types of VRLA

AGM (Absorbed Glass Mat) Batteries AGM batteries are similar to VRLA batteries. A boron silicate fiberglass mat acts as a separator between the electrodes and absorbs the free electrolyte. The main purpose of this type of battery is to recombine the hydrogen and oxygen generated during the charging process. The fiberglass mat absorbs and immobilizes the electrolyte, but keeps it in a liquid rather than a gel form. In this way, the electrolyte is more readily available to the plates allowing faster reactions between the electrolyte and the plate material which gives higher charge/discharge rates as well as deep cycling capability. AGM batteries are very robust and can withstand severe shock and vibrations. Also, the self-discharge rate is low, typically 0.25–0.75% per month. They are also called “starved electrolyte” or “dry” batteries because the fiberglass mat is 95% saturated with the electrolyte and there is no excess liquid [4].

Gel Cell The gel cell is similar to the AGM battery, except that the electrolyte is gelled to immobilize it. The electrolyte is mixed with a silica compound to create the gelled solution. It uses an alternative recombinant technology to promote recombination of the gases produced during charging. It also reduces the possibility of spillage of the electrolyte. Charging rates are limited, because overcharging may cause excess of gases to be released causing damage. The gel cell cannot be fast charged on a conventional automotive charger since it can cause permanent damage [4].

Choosing a Battery

The ideal EV battery should have a constant output voltage at any value of current drawn over the entire state-of-charge (SOC) range and it should also accept

high charge rates at the same voltage. No battery has such ideal characteristics but the suitability of a battery for EV use can be determined by the ratio of charging voltage to discharging voltage over the range of SOC and current [9].

Given below are the important factors to consider while choosing a battery for EV use.

Power Battery power performance is generally specified by manufacturers as W/kg at either 2/3 or 1/2 of the open circuit voltage. This ignores the ratio of the terminal voltage under load to that during charge or regenerative braking which is the relevant parameter for EV applications. A more useful figure of merit for comparing the power performance of EV batteries is the power density (W/kg) at 75% end-of-charge voltage (V_{eoc}). For example, if the battery voltage of an EV drops below 75% of V_{eoc} during acceleration, it means that the battery is operating at low cycle efficiency. Another consideration is the cost of the vehicle drive train which is proportional to the product of the maximum voltage rating and the current rating. A low power battery needs more expensive drive train components to achieve a given level of performance because it needs higher current to extract the same power at a lower voltage. A high power battery not only increases vehicle performance but it reduces the cost of the motor and electronics for equivalent performance.

Energy Energy capacity of an EV battery determines the vehicle range. The two parameters which are commonly used to specify energy capacity are specific energy and energy density. Reducing energy consumption is often a better way to increase EV range than increasing battery capacity. EV batteries cannot yet match the energy density of gasoline but provide power to exceed the acceleration of conventional vehicles. One of the unique features of EVs is the capability to provide high peak power and excellent acceleration without sacrificing operating efficiency [9]. The Tesla Roadster sports car demonstrates this by operating at 180 Wh/mile in normal driving and offering acceleration from 0 to 60 mph in 3.7 s, which is quicker than a gasoline-powered Mercedes-Benz SLR McLaren. The first-generation EV1 used Delphi's valve-regulated lead acid batteries, which is capable of operating at 164 Wh/mile. Nickel metal hydride batteries (NiMH)

batteries (See section “[Nickel-Cadmium Battery](#)”) have twice the energy density and specific energy compared to lead acid batteries. An EV fitted with a NiMH battery which is of the same size and weight as a lead acid battery has twice the range. However, due to power considerations, it is not necessary that an EV could be built to match the range of a lead acid battery powered EV using a NiMH battery with half the size and weight [9].

Cost Although lead acid batteries have less energy density and specific energy and are bulkier compared to NiMH and lithium-ion batteries, they are typically inexpensive. Today, a lead acid battery pack for an EV costs \$215/kWh, a NiMH battery costs \$350/kWh, and a lithium-ion battery costs \$400/kWh [9]. The lower cost of the lead acid battery makes it an affordable technology and also decreases the overall cost of EVs. Axion Power, a firm based in Pittsburgh, Pennsylvania, has come up with a new technology called lead-carbon battery which is derived from traditional lead acid battery technology. Axion Power has managed to convert a pickup truck to run on a pack of the lead-carbon battery for around \$8,000 [10]. If further cost reductions are achieved in the production of batteries, then EV pricing can become competitive with conventional vehicles.

Temperature Effects on Batteries Batteries function because of electrochemical reactions (charging and discharging) taking place in the cell. These chemical reactions are dependent on temperature. Nominal battery performance is usually specified for working temperatures between 20°C and 30°C. However the actual performance can deviate substantially if the battery is operated at higher or lower temperatures. The operation of any battery generates heat due to the I^2R losses as current flows through the internal resistance of the battery whether it is being charged or discharged. This is also known as electrical heating or Joule heating. During discharge, since the total energy within the system is fixed, the temperature rise is limited by the available energy. Another factor which affects the performance of a battery is the ambient temperature. If the ambient temperature is higher than the temperature of the battery, the battery gains heat from the surrounding

and if the ambient temperature is lower, the battery losses heat to the surrounding. The difference in the ambient and the optimal operating temperature of a battery reduces its performance. Overheating may also be caused in batteries because of highly exothermic reactions, which generate a lot of heat and may ultimately damage the batteries [4].

Lead acid batteries are exothermic during charging, which makes their temperature rise dramatically. If the temperature exceeds beyond a limit, the battery may be damaged. Also, being a galvanic cell, its internal resistance is temperature dependent. Internal temperature decreases as the temperature rises due to the increase in electron mobility. The cell is very inefficient at low temperatures but the efficiency improves at higher temperatures due to the lower internal impedance and also because of the increased rate of chemical reactions. However, the lower internal resistance also causes the self-discharge rate to increase. Additionally, the cycle life deteriorates at high temperatures. Some form of heating and cooling is therefore required to maintain the battery within a specific temperature range to achieve optimum performance [4].

Life Battery life represents an important parameter in battery performance that affects customer satisfaction and overall cost. Battery life depends mainly on the number of cycles. Technical factors such as temperature control, charging procedures, and exposure to abusive conditions also play an important role in determining the battery life. Lead acid batteries in EVs may last 15,000–30,000 cycles if used regularly. However, they start deteriorating after 2 years regardless of the kind of use. Lead acid batteries respond well to battery management systems that control temperature and maintain SOC equalization. A factor related to battery life is the battery residual value. Although virtually all EV batteries are recycled for economic and environmental reasons, EV batteries may retain value greater than their salvage value after their useful life as a traction battery is complete. AC Propulsion regularly sells spent traction modules as starter batteries with a 2-year warranty for \$25 or about \$50/kWh. These modules are retired because their capacity is diminished by 30% or more, but they serve well as starter batteries [9].

Table 2 below shows some typical specifications of VRLA batteries used in EVs.

Battery Technologies. Table 2 Specifications of VRLA batteries in EVs [11, 12]

Electric vehicle	1998 Ford Ranger EV	GM EV 1, first model
Manufacturer	Delphi	Delphi
Number of modules	39	26
Weight of module (kg)	19.3	18.8
Nominal module voltage (V)	8	12
Nominal system voltage (V)	312	312
Nominal capacity (Ah)	60 (100% capacity)	53 (50% capacity)
Specific energy (Wh/kg)	23.7–25.2	26.3–31.9
Efficiency (Wh/mile)	237–356	115–164

Lead Acid Battery Circuit Model

Consider Fig. 5 as a lead acid cell model. We construct this circuit using PSpice software. Consider the cell to provide 2 V nominal voltage, 10 Wh capacity, round-trip efficiency of 90%, and 70% initial state of charge. Here, available energy during operation is computed as

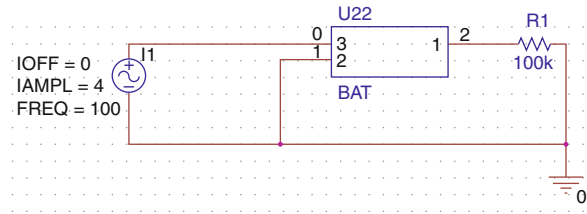
$$\text{SOC}(t) = \text{SOC}_{\text{initial}} + \frac{1}{\text{Capacity(Wh)}} \int \frac{kV_1 I_{\text{bat}}}{3600} dt$$

where k is cell efficiency, V_1 is cell voltage, and I_{bat} is cell current. During discharge, current flows in the opposite direction when compared to charging, leading to a minus sign before the integral. Division by 3,600 is needed to ensure that cell capacity is in units of watt-hours, Wh. Alternate charging and discharging operation is conducted by applying AC current I_{AC} at 4 A, 100 Hz, as shown in Fig. 16. Resistor R_1 is chosen arbitrarily high to ensure there is no voltage drop at the cell's output terminals.

Figure 6 shows the state of charge (SOC) of the cell.

Note that the Y-axis provides state of charge as a percentage. Figure 7b provides cell voltage V_1 , whereas I_{AC} is shown in 7a.

Note that in addition to the nominal 2 V, cell voltage is a function of state of charge of the cell. For example, a certain degree of overvoltage can occur with high state of charge. A 70% state of charge leads to a cell (over) voltage of 2.1 V in 7b.

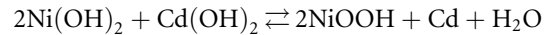


Battery Technologies. Figure 5
Lead acid cell model using PSpice

When I_{AC} is positive, current travels into the cell, simulating charging. This is evident in Fig 18b where V_1 drops while I_{AC} increases in the positive direction. Negative I_{AC} implies cell discharge, with V_1 above the nominal 2 V. An immediate advantage of lithium-ion batteries is their diversity in operation. Figure 19 shows only a few possible chemical combinations.

Nickel-Cadmium Battery

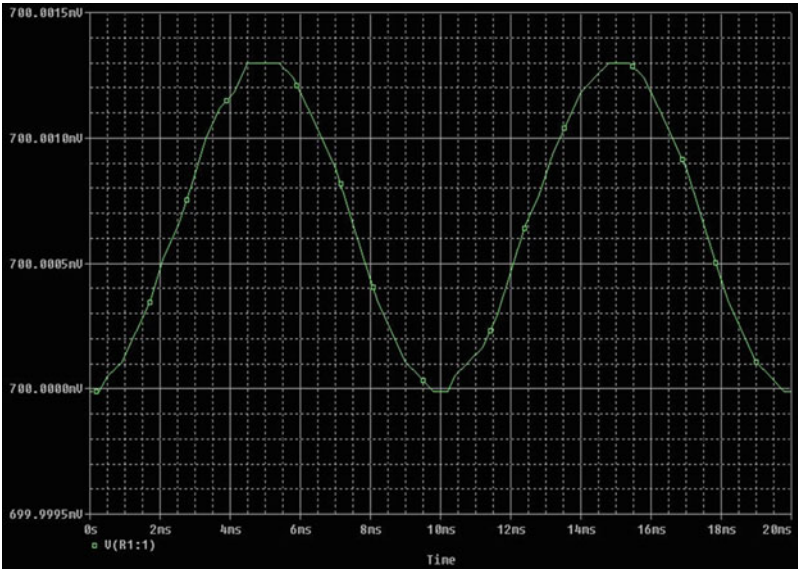
The nickel-cadmium battery commonly abbreviated as NiCd battery is a type of rechargeable battery which works by oxidizing nickelic hydroxide ($\text{Ni}(\text{OH})_2$) into nickelous hydroxide (NiOOH) and has metallic cadmium as electrodes. The charge/discharge reaction can be given as follows:



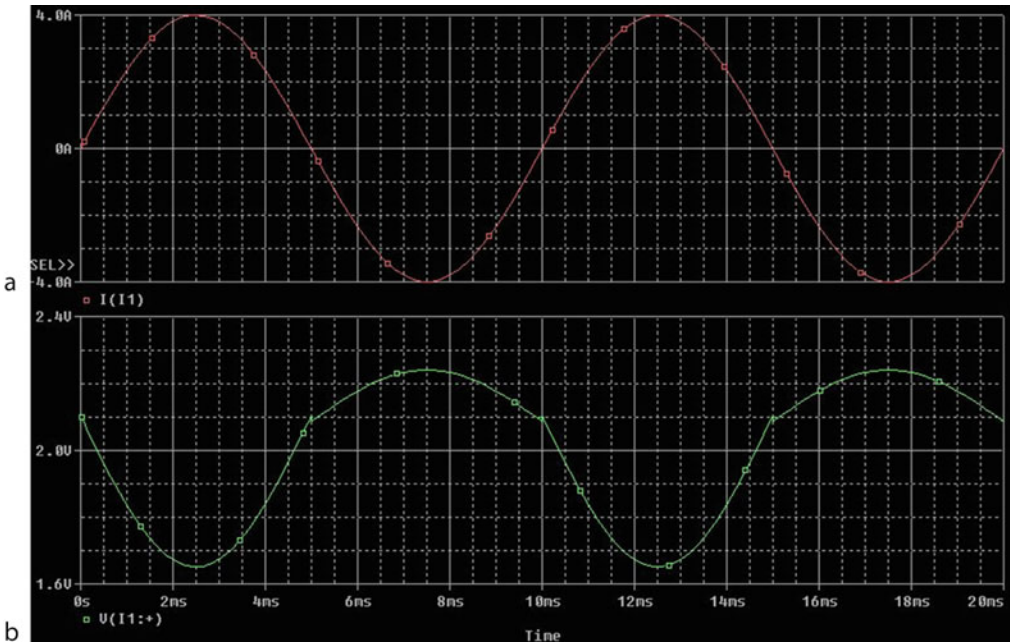
The features of this battery are that the electrolyte does not take part in any of the chemical reactions and the active materials are insoluble in the electrolyte. Nickel-cadmium batteries have a reputation for their robustness, reliability, and service life. They can also operate under severe weather conditions, with operating temperatures ranging from -40°C to $+60^\circ\text{C}$ (because the electrolyte has a very low freezing point), excellent cycling capability (up to 2,000 cycles at 80% depth of discharge), long storage life, and low or zero maintenance [10, 11].

NiCd batteries have been used extensively in consumer electronics and power tools. In the recent past, NiCd batteries have also been used in electric vehicles, an example being the Peugeot 106 electric, which used NiCd batteries manufactured by SAFT [12].

Nickel-cadmium cells have a nominal cell potential of 1.2 V. This is lower than the 1.5 V of many popular primary cells, and consequently they are not



Battery Technologies. Figure 6
Cell state of charge



Battery Technologies. Figure 7
Applied AC current and cell voltage

appropriate as a replacement in all applications. NiCd batteries have an energy density of 40–60 Wh/kg, which is greater than that of lead acid batteries, but less when compared to NiMH and Li-ion batteries [14].

Advances in battery-manufacturing technologies throughout the second half of the twentieth century have made batteries increasingly cheaper to produce; about 1.5 billion NiCd batteries were produced

annually up until 2000. NiCd batteries never became widely used as a replacement for lead acid batteries in the areas where those batteries dominate, mainly because of the toxic nature of the battery and the reduction in its capacity as the battery ages. However, NiCd batteries had an overwhelming majority of the market share for rechargeable batteries in consumer electronics up until the mid-1990s [10].

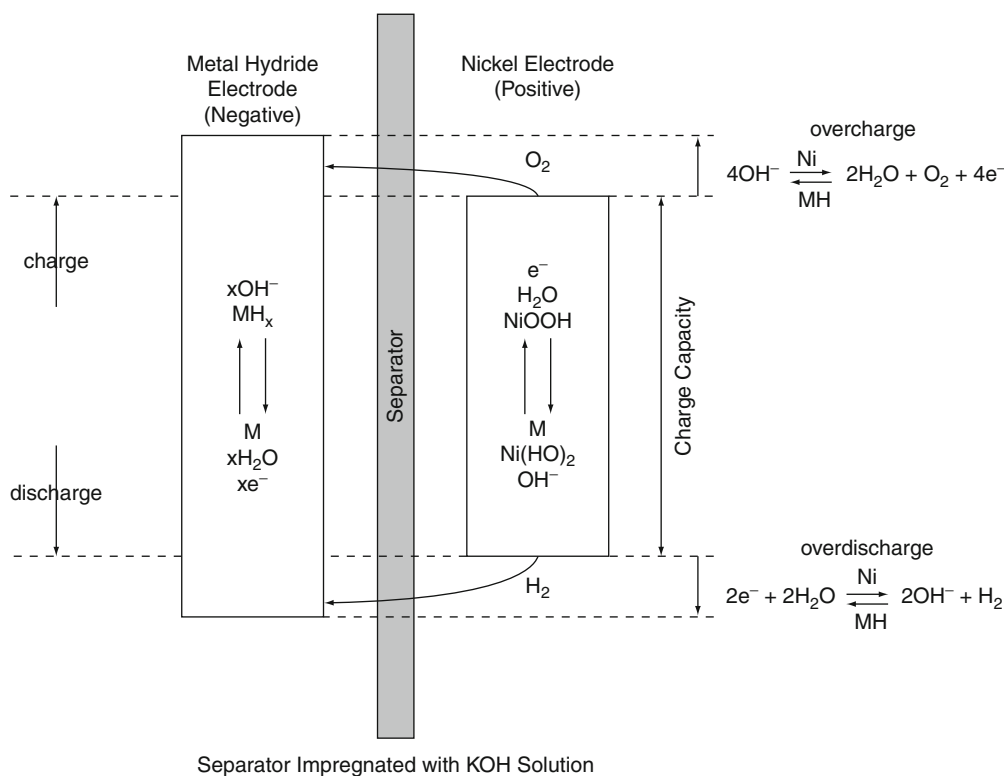
Nickel Metal Hydride Batteries

Nickel metal hydride (NiMH) batteries were first developed in the late 1980s and ever since have been used in portable electronic devices like camcorders, power tools, and cell phones. NiMH batteries have high storage capacity and relatively high ramp rates. They have succeeded lead acid batteries owing to higher number of cycles and higher energy density [14]. A study by EPRI in 2004 showed that NiMH batteries are acceptable for full-function EVs, city EVs, and plug-in hybrid electric vehicles (PHEVs) [8].

Although the technology was largely driven by military and government research in its earlier days, recently, significant contributions have been made by EV manufacturers. Applications of NiMH EV batteries include all PHEVs manufactured by General Motors, Honda, Ford, Toyota, and the Vectrix scooter, among others. The town of Nice, France, now operates its low floor tram, manufactured by Alstom using NiMH batteries. Honda's humanoid prototype robot ASIMO is another application.

Nickel Metal Hydride Cell Construction and Chemistry

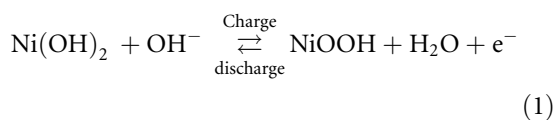
The basic representation of a NiMH cell is shown in Fig. 8. The positive electrode of a NiMH cell consists of a spongy mass of nickel hydroxide $\text{Ni}(\text{OH})_2$. During charge, the positive electrode releases hydrogen into the electrolyte, which in turn combines with hydroxide (OH^-) ions. This reaction results in nickel oxyhydroxide (NiOOH) on the positive electrode and water (H_2O) in the electrolyte plus one free electron, e^- .



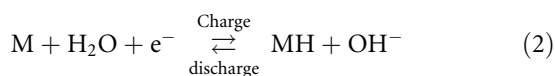
Battery Technologies. Figure 8

Schematic representation of a NiMH cell [7]

The equation for the positive electrode can be given by:



The negative electrode contains a metal alloy-hydride complex. In an exothermic reaction, the water (H_2O) from the electrolyte combines with the free electron to form metal hydride (MH) and hydroxide (OH^-). The metal alloy absorbs and desorbs the hydrogen, allowing the electrochemical reaction to occur without producing hydrogen gas. Equation 2 shows the net chemical reaction that occurs at the negative electrode during charge and discharge.

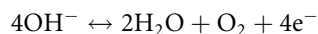


The most commonly used electrolyte is a solution of aqueous potassium hydroxide, KOH, in which the KOH concentration ranges from 25% to 40% by mass. The two equations show that there is no net change in electrolytic quantity. This result contrasts with other electrolyte systems like NiCd, where water is generated at both electrodes during charge and consumed at both electrodes during discharge. Although transient electrolyte concentration gradient occurs in NiMH batteries, its constant average concentration has good overall performance in gas recombination, kinetics, high and low temperature operation, and resistance to cycle life limitations caused by corrosion and swelling [7].

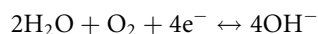
Overcharge and Over-discharge Reactions

The NiMH battery has overcharge and over-discharge reactions that allow the battery to handle abuse conditions of overcharge and over-discharge without adverse effects. The reaction that takes place at the two electrodes during overcharge is an oxygen recombination reaction. It can be shown as follows:

At the positive (Ni) electrode OH^- ions are oxidized generating oxygen:



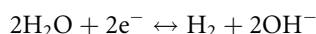
At the negative (MH) electrode the oxygen is reduced:



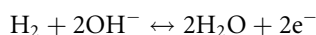
The net result is generation of heat which is proportional to the energy input. This occurs at the expense of increasing the stored charge in the battery. If the rate of charge input exceeds the rate of recombination, the cell pressure increases, which may lead to cell damage.

During over-discharge, hydrogen is released at the positive electrode and recombined at the negative electrode. The reactions are as follows:

At the positive electrode, water is reduced and hydrogen gas is released:



The hydrogen gas is then oxidized at the negative (MH) electrode:



The ability of the NiMH cell to tolerate over-discharge is very important for large series strings of batteries since capacity mismatches may cause some cells to over-discharge. To ensure that the overcharge and over-discharge reactions function properly and thus control the buildup of cell pressure, the NiMH battery is constructed with the Ni electrode as the capacity limiting electrode and the MH electrode with excess capacity to allow recombination reactions to take place during overcharge and over-discharge [7].

Types of NiMH Batteries

The earliest pioneering work on NiMH batteries was performed at the Battelle-Geneva Research Center starting after its invention in 1967. These batteries showed high specific energy up to 50 Wh/kg, power density up to 1,000 W/kg, and a reasonable deep cycle life of 500 cycles (depth of discharge: 100%). Due to the inherent deep cycling capability and the high specific energy, NiMH batteries have been used in EVs. The two major types of NiMH batteries used today are the cylindrical batteries and the prismatic batteries. The next section describes the cylindrical NiMH batteries in detail giving the battery structure and the battery characteristics. The later section describes prismatic NiMH batteries and gives the comparison between the two of them. Currently, there are over two million HEVs running worldwide, which use NiMH batteries [15].

Cylindrical NiMH Cell

Battery Structure The single cell shown in Fig. 9 is a sealed cylindrical battery of D-size with a diameter of 32 mm and a height of 60 mm. A sealing plate is equipped with a valve to prevent bursting with an increase in internal pressure. The battery case is made of steel and both positive and negative electrodes are coiled and separated by a separator. This battery optimizes the reaction area of the electrodes, reducing resistance for current collection and improving electrolyte composition to obtain high power characteristics. The nominal battery capacity is 6.5 Ah and the maximum output power is more than 100 W per cell. To reduce the internal resistance and shield against vibrations, disk plates are inserted for cell connection [13].

Battery Characteristics Table 3 gives the characteristics of a single cylindrical cell and battery consisting of six cells.

Discharge Power Characteristics Figure 10 shows the specific power characteristics of a battery module that consists of six cells at different state of charge (SOC). The module provides 800 W in 2 s and 650 W in 10 s. As seen in the graph, for a given range of charge capacity, the specific power is almost constant. Also, for the 50% SOC and 100% SOC, there is not much variation in specific power, giving 650 W/kg in 2 s and 600 W/kg for a 10 s duration. Relatively constant input and output power is highly desired by EV manufacturers. It can be

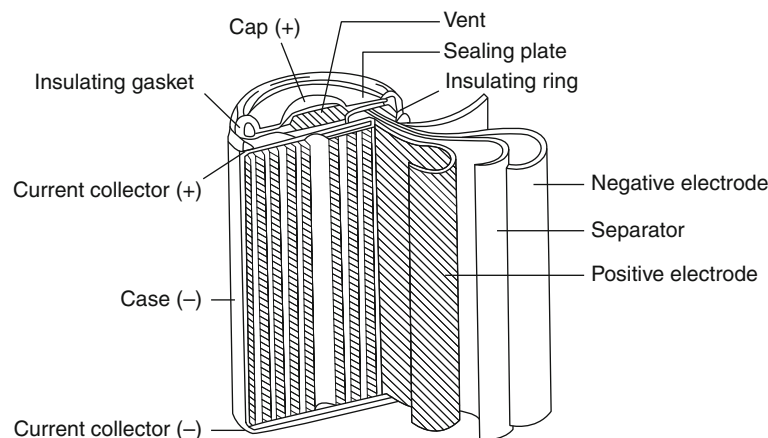
clearly seen from the graph that NiMH prismatic batteries deliver an almost constant power for any SOC, which is highly desirable in batteries for EVs.

Charge Efficiency For practical use, high charge efficiency is required over a wide temperature range. Figure 11 shows the battery has a very high charge efficiency, which provides high regenerative acceptability over the SOC range, mostly used during normal vehicle operation. The ampere-hour charge efficiency is nearly 100%. Also because of the very small energy loss, heat generation of the battery is minimized.

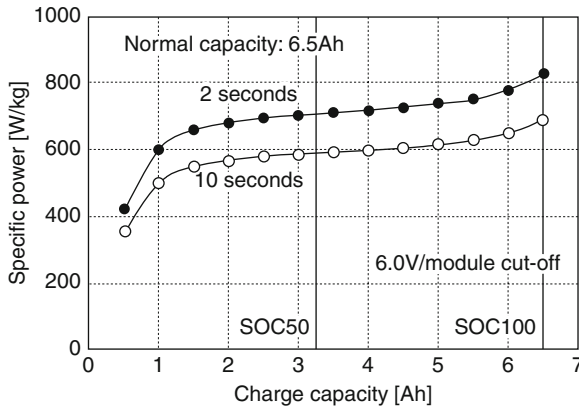
Life Cycle Characteristics To preserve an active battery system, flow of power in and out of the battery needs to be maintained, even if minimal. The battery's

Battery Technologies. Table 3 Characteristics of a single cylindrical cell and battery consisting of six cells [13]

	Single cell	Battery module (six cells)
Output power	625 W/kg, 2,160 W/l	600 W/kg, 2,070 W/l
Input power	500 W/kg, 1,720 W/l	480 W/kg, 1,660 W/l
Energy density	45 Wh/kg, 172 Wh/l	43 Wh/kg, 161 Wh/l
Nominal voltage	1.2 V	7.2 V

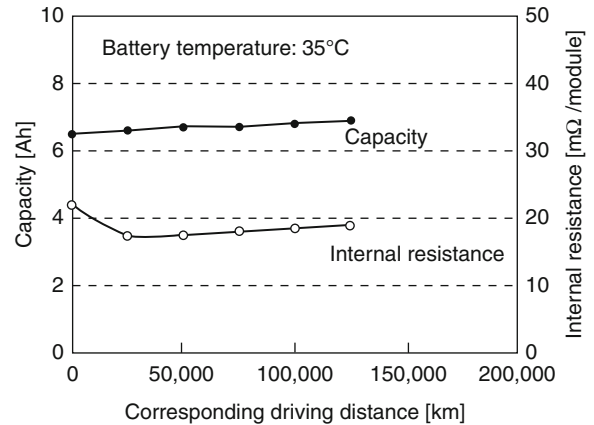


Battery Technologies. Figure 9
Structure of a cylindrical battery



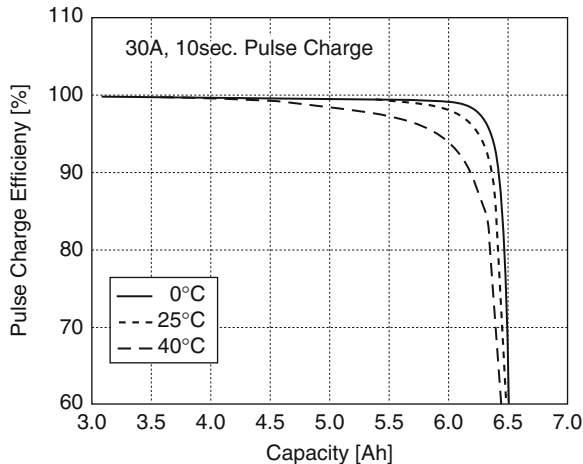
Battery Technologies. Figure 10

Specific power of a cylindrical battery at different state of charge levels [13]



Battery Technologies. Figure 12

Life cycle characteristics of cylindrical battery module with simulated actual driving pattern [13]



Battery Technologies. Figure 11

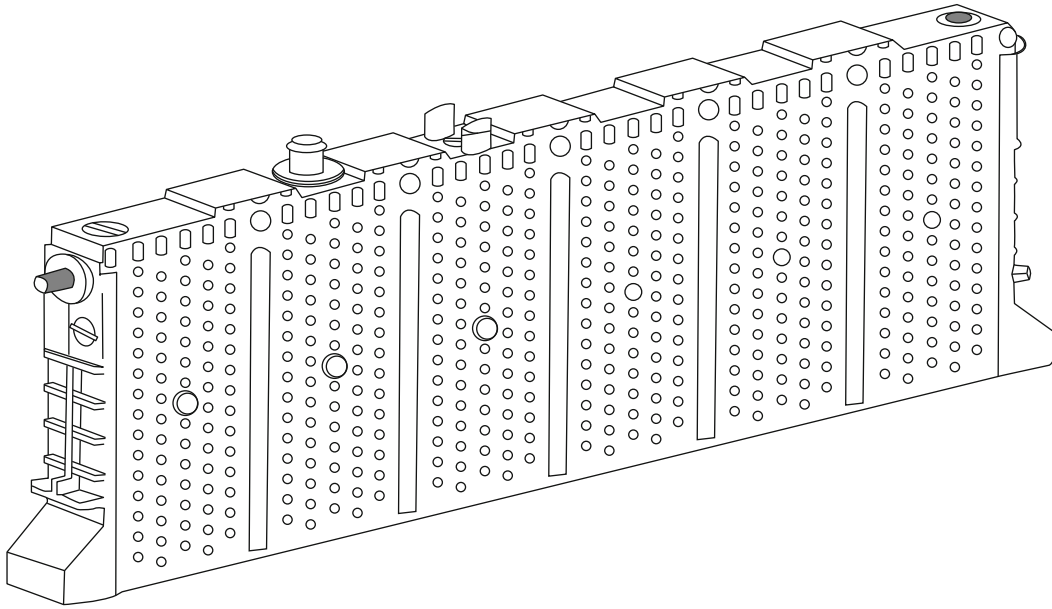
Pulse charge efficiency of cylindrical battery module at different temperatures [13]

controller needs to ensure that the battery is neither fully charged nor completely discharged. To test such operating conditions, a life test was conducted at Panasonic's test facility in Shizuoka, Japan. One example of the results is shown in Fig. 12 [13]. The test provides results in which the input and output power simulate real vehicle driving at 35°C. As a result, the durability was found to be equivalent to more than 100,000 km driving without deterioration of battery characteristics.

Prismatic NiMH Battery

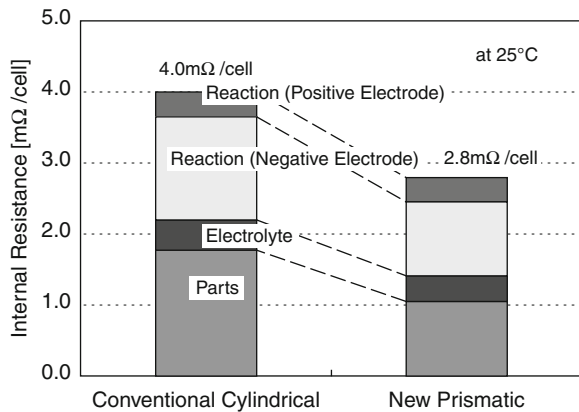
Structure To improve power, reduce the number of connected parts. Figure 13 shows the appearance of a prismatic module design consisting of six cells in series. The conventional cylindrical module has connecting plates to connect cells and plastic insulating rings to prevent external short circuits. The prismatic module adopts internal connection; therefore, connecting plates and plastic insulating rings are not required. As a result, a shorter current path is accomplished. The investigation of electrode dimensions and current collector design shows that the current flow path is shortened. By thinning the positive and negative electrodes, the number of electrodes are increased, which increases the reaction area and decreases the current density. Resin material is used to make the battery case, which provides increased safety and reliability. The resin material makes it easy to design bumps and ribs on the side of the battery case. The bumps and ribs provide cooling and also reduce the pack volume by 40%. The resin also reduces 20% of the prismatic battery's weight compared to a cylindrical battery pack. The six cells are internally connected to form one module. External connection parts like bus bars and connecting plates are also not required [13].

Figure 14 shows the improved power characteristics and reduced internal resistance of this battery, as compared to the cylindrical battery. The main source of the



Battery Technologies. Figure 13

Prismatic NiMH battery [13]



Battery Technologies. Figure 14

Internal resistance of prismatic and cylindrical battery cell before activation [13]

reduction in internal resistance is the components. A high specific power of 1,000 W/kg, which is higher than that of the conventional cylindrical battery, is also achieved.

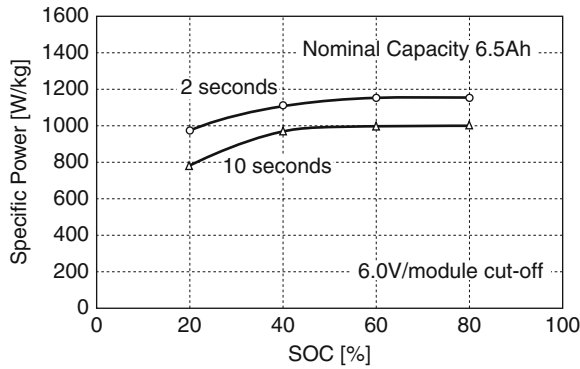
Table 4 shows the module characteristics of both prismatic and cylindrical battery types. It is clear that the prismatic design is superior to the cylindrical design.

Battery Technologies. Table 4 Comparison between prismatic and cylindrical battery modules [13]

	Prismatic module	Cylindrical module
Dimensions (mm)	19.6 × 106 × 275 (width × height × length)	35 × 384 (diameter × length)
Nominal voltage (V)	7.2	7.2
Nominal capacity (Ah)	6.5	6.5
Specific power (W/kg)	1,000	600
Specific energy (Wh/kg)	46	43
Weight (g)	1,020	1,090

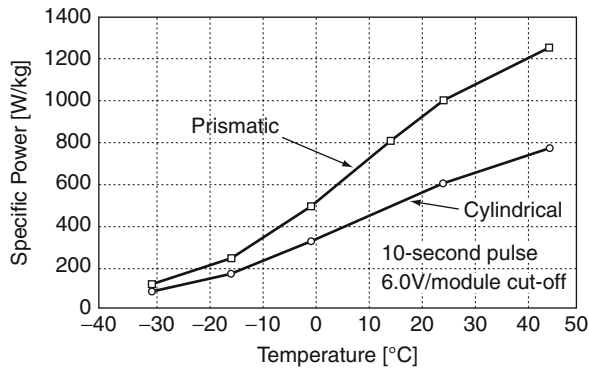
Discharge Power Characteristics Figure 15 shows the power characteristics of the prismatic module at different SOC. This battery provides 1,000 W of power per kilogram for 10 s and 1,150 W of power for 2 s with the SOC maintained in a range 40–60%. It also has high power density at low SOC; about 800 W/kg for 10 s and 1,000 W/kg for 2 s at 20% SOC.

Figure 16 shows the power characteristics at different temperatures for the cylindrical battery and



Battery Technologies. Figure 15

Specific power of prismatic battery at different SOC [13]



Battery Technologies. Figure 16

Specific power of prismatic and cylindrical battery module at different temperatures [13]

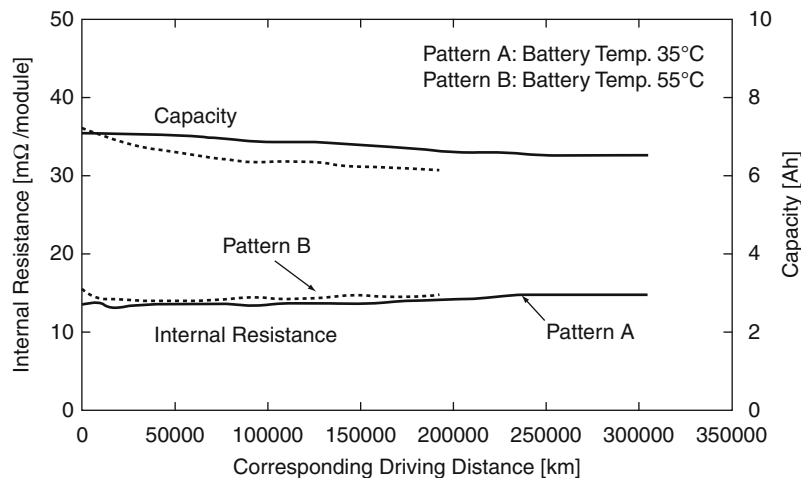
the prismatic battery. As seen, the characteristics of the prismatic battery are better (490 W/kg at 0°C and 120 W/kg at -30°C). Also the temperature where power discharge of 200 W/kg is possible is reduced by about 10°C as compared to the cylindrical battery.

Life Characteristics of Prismatic Batteries In Fig. 17, Pattern A represents a normal driving profile, with a maximum SOC deviation of 15% and pattern B represents a high load driving profile with a maximum SOC deviation of 30%. After tests corresponding to a driving distance of 300,000 km with pattern A at 35°C, there was no deterioration observed in battery performance. Also, with pattern B at 55°C, the battery was able to achieve a driving distance of 200,000 km [13].

Figure 18, above, shows the EV-95 (95 Ah) and EV-28 (28 Ah) units developed by Panasonic for EVs. EV-95 has long life characteristics of more than 1,000 cycles and 4 years of onboard driving [13].

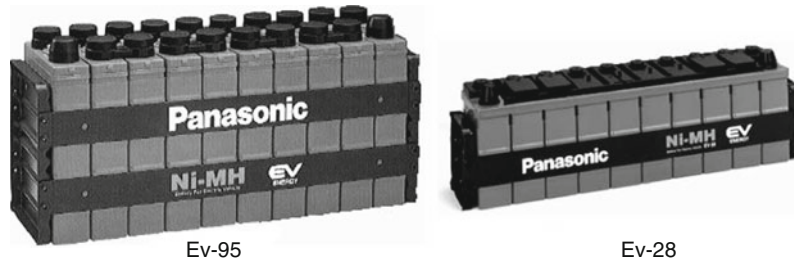
The batteries shown above have the following characteristics:

1. Optimization of additives (Y_2O_3) for excellent charge efficiency of the positive electrodes
2. $MnNi_5$ system of hydrogen-absorbing alloy for the negative electrodes
3. High performance, hydrophilic-treated polypropylene separator



Battery Technologies. Figure 17

Life cycle characteristics of prismatic batteries [13]



Battery Technologies. Figure 18
EV-95 and EV-28 batteries by Panasonic

The electrode groups consist of alternately stacked positive electrodes and negative electrodes interleaved with separators. Inserting these electrode groups into a resin battery case and sealing with a cover equipped with a valve after filling with alkaline electrolyte forms the cell. A battery module consists of ten cells connected in series by metal plates and these are configured to permit airflow between the cells to ensure a uniform temperature distribution.

Table 5 gives the characteristics of the EV-28 and EV-95 batteries manufactured by Panasonic.

Below is Table 6, which gives characteristics of NiMH batteries, produced by Texaco Ovonic Battery Systems and VARTA.

The second-generation GM EV1 used NiMH batteries. Table 7 shows the specifications of that battery.

Lithium-Ion Batteries

Lithium-Ion Battery Chemistry

Lithium is the least dense of all solid metals, has the greatest electrochemical potential, and provides the largest energy density by weight. For many years, lead acid had been the predominant battery for large-scale equipment. G. N. Lewis pioneered early work with lithium-ion battery technology but it was not until the early 1970s before it became commercially viable. Because of the inherent instability of lithium metal, early attempts at rechargeable batteries failed. Research then shifted to lithium-ion-based composites which, although less dense, are safer to use. Lithium-ion batteries emerged during the early 1990s. Today, lithium-ion is the fastest growing and most promising battery chemistry.

Battery Technologies. Table 5 Basic characteristics of the EV-28 and EV-95 batteries [13]

	EV-28	EV-95
Dimensions (width × height × length) mm × mm × mm	75 × 110 × 388	116 × 175 × 388
Nominal voltage (V)	12	12
Nominal capacity (Ah)	28	95
Weight (kg)	6	18.7
Specific energy (Wh/kg)	58	65
Specific power at 80% depth of discharge (W/kg)	300	200
Self discharge at 45°C, 1 month (%)	20	20
Cycle life at 25°C ambient temperature, 80% DOD (cycles)	>1,000	>1,000

Battery Technologies. Table 6 Battery characteristics [8]

Manufacturer	Battery design	Cell size (Ah)	Specific energy (Wh/kg)	Specific power (W/kg)
Texaco Ovonic battery	High power	7.5	~40	650
	Medium power	28	48	~440
	Medium power	45	71	~390
VARTA	High power	10	30	630
	Medium power	45	50	220

Battery Technologies. Table 7 GM EV 1 (generation 2) battery specification [16]

Manufacturer	Ovonic energy products
Type	Nickel metal hydride
Number of modules	26
Weight of module	18.3 kg
Weight of pack(s)	481 kg
Nominal module voltage	13.2 V
Nominal system voltage	343 V
Nominal capacity (50% charge capacity)	85 Ah

As mentioned earlier in section “[Basic Characteristics of Batteries](#),” a battery functions as a combination of chemical reactions, oxidation at the anode (where electrons are generated in discharge mode), and reduction at the cathode (at which electrons enter the cell). Depending on the direction of the current (charge or discharge) each electrode is either the cathode or the anode. The electrolyte can serve as a reaction propellant or even as an integral part of the reaction. This combination of reactions is referred to as *redox*. [Table 8](#) provides redox reaction potentials for eight elements.

Lithium and fluoride generate the highest potential during oxidation and reduction, respectively [7]. A significant advantage of lithium-ion batteries is their efficiency in charge retention and energy supply. The internal resistance of lithium-ion cells is comparatively low, which means they do not lose a considerable amount of energy as heat (I^2R loss) [8]. In general, the internal resistance of a cell is modeled as a resistor in series with an ideal voltage source. Maximum efficiency occurs with a low internal series resistance and a large load resistance. Maximum power can be extracted from a cell when load resistance is equal to the cell's internal resistance. Under this condition half the total power is expended as heat, while the other half is available for use. The availability of high power output is a useful property for lithium-ion cells, especially when instantaneous power is required. Consider the example of a race car looking to set a new

Battery Technologies. Table 8 Redox potential [7]

Electrode reaction	Potential (V)	Electrode reaction	Potential (V)
$\text{Li}^+ + e \leftrightarrow \text{Li}$	−3.01	$\text{Cu}^{2+} + 2e \leftrightarrow \text{Cu}$	0.34
$\text{Na}^+ + e \leftrightarrow \text{Na}$	−2.71	$\text{Ag}^+ + e \leftrightarrow \text{Ag}$	0.80
$\text{Ni}^{2+} + 2e \leftrightarrow \text{Ni}$	−0.23	$\text{Cl}_2 + 2e \leftrightarrow 2\text{Cl}^-$	1.36
$\text{Pb}^{2+} + 2e \leftrightarrow \text{Pb}$	−0.13	$\text{F}_2 + 2e \leftrightarrow 2\text{F}^-$	2.87

quarter-mile speed record. This car would need high instantaneous power without regard to cell degradation due to overheating.

Operation

Numerous lithium-based alloys are available for use as anode. Lithium polymers are considered commercially safe, while metallic lithium is still at the developmental stage [17]. Charge flow for any of the combinations in [Fig. 19](#) is typically the same, as shown in [Fig. 20](#).

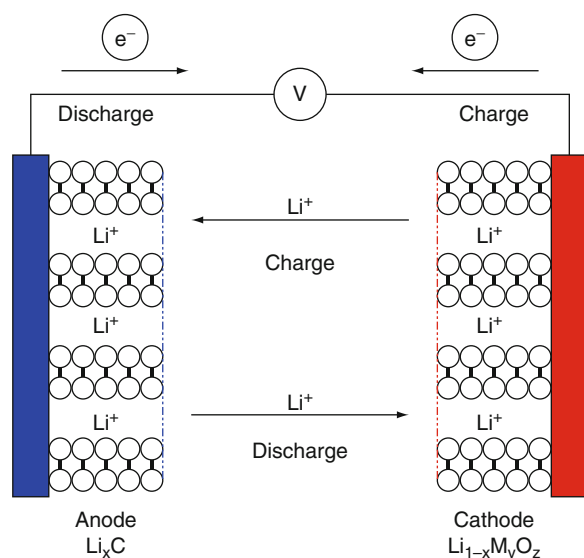
A common electrolyte is lithium hexafluorophosphate (LiPF_6). It was chosen for its high redox potential. Ehsani et al. [17] mentions that LiPF_6 is unstable under high heat and moisture. Hydrofluoric acid (HF) is produced as a by-product to the electrolyte's reaction with water. For this reason, there was significant opposition to its use in the early 1990s. Since then however, it has been revealed that a small amount of HF increases life cycle, because of the formation of a strong passive layer on the cathode.

The addition of HF prevents formation of lithium dendrite. (Most metals are combined with alloys for dexterity and strength. Due to the presence of alloys, the metal tends to exist in a nonuniform, snowflake-like distribution called *dendrite*.) LiPF_6 is also easily soluble in the solvent, making it a good solid interface on the surface of anode materials. Lithium-ion is considered to be the current generation technology for EV batteries, in part because of its high energy density. Also, lithium has the highest redox reaction potential of any metal. It is also necessary to consider the fact that key elements of lithium-ion batteries are facing exhaustion. Cobalt metal, used for cathode, has been in shortage for quite some time [17]. Most metals are combined with alloys for dexterity and strength. Due to the presence of alloys, the metal tends to exist in a, nonuniform, snowflake-like distribution called dendrite [17].

Anodes	Electrolytes	Cathodes
<div> <div>Metallic Lithium</div> <div>Lithium Alloys</div> <div>Primary Batteries</div> </div>	Liquid Organic Electrolytes	<div> $\text{Li}_{1-x}\text{Ni}_{1-y-z}\text{Co}_y\text{M}_z\text{O}_4$ (M=Mg, Al, etc) </div>
<div> <div>Lithiated Carbons</div> <div>Graphites</div> <div>Other Carbons</div> </div>	Solid Polymer Electrolytes	<div> $\text{Li}_{1-x}\text{Co}_{1-y}\text{M}_y\text{O}_2$ </div> <div> $\text{Li}_{1-x}\text{Mn}_{2-y}\text{M}_y\text{O}_4$ </div>
<div> <div>Other Lithiated Materials</div> <div>Composite Alloys</div> <div>Sn(O)-based</div> <div>Sn(M)-based</div> </div>	Polymer Gel Electrolytes	<div> Polyanionic Compounds $\text{Li}_{1-x}\text{VOPO}_4\text{:Li}_x\text{FePO}_4$ </div>
<div> <div>3d Metal Oxides: Nitrides</div> </div>	Ionic Liquids	<div> $\text{Li}_{1-x}\text{Mn}_{1-y}\text{M}_y\text{O}_2$ (M=Cr, Co, etc) </div>

Battery Technologies. Figure 19

Numerous chemical combinations for lithium-ion batteries

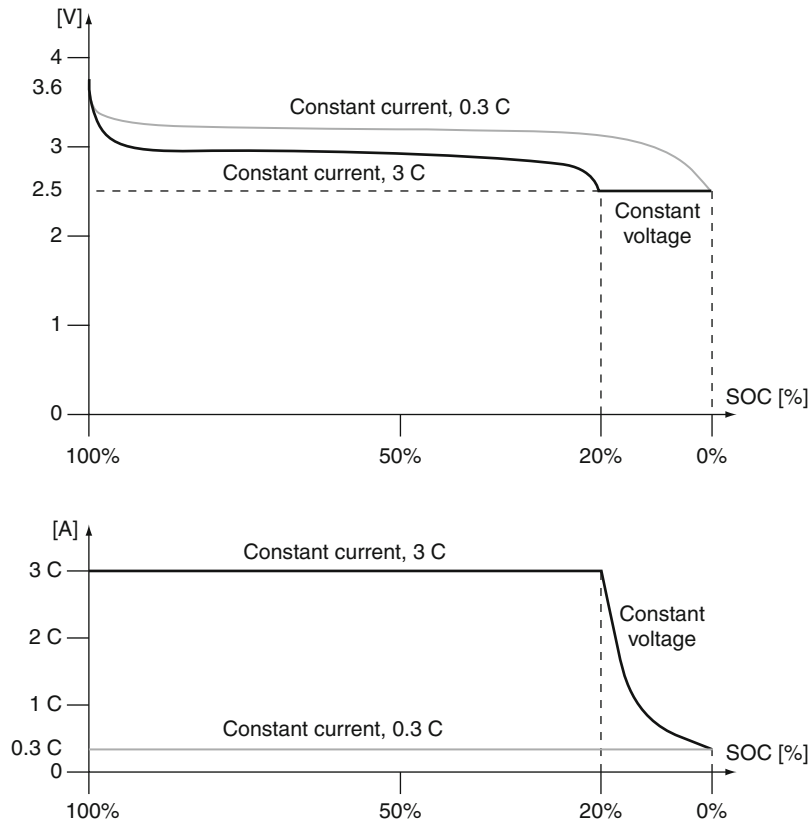


Battery Technologies. Figure 20

Charge flow for lithium-ion batteries [17]

Efficiency

Lithium-ion batteries are practically 100% charge efficient, according to Brodd et al. [5]. In essence, all the charge lost during discharging is recovered during charging. Note that there is a net loss in energy during each complete charging/discharging cycle. This is because the cell voltage is lower during discharging as compared to the charging cycle. Figure 21 provides discharge curves for voltage and current of a lithium-ion cell. Note that the voltage continues to drop during discharge before stagnating at a constant level toward the end of charge availability. This constant voltage can be attained by discharging at a lower current, as shown in the current curve of Fig. 21. As the current drops to zero, the total charge from the cell adds up to the same value regardless of the rate of discharge (whether the discharge was at a low current or at a high current) [5].



Battery Technologies. Figure 21

Voltage and current during discharge [18]

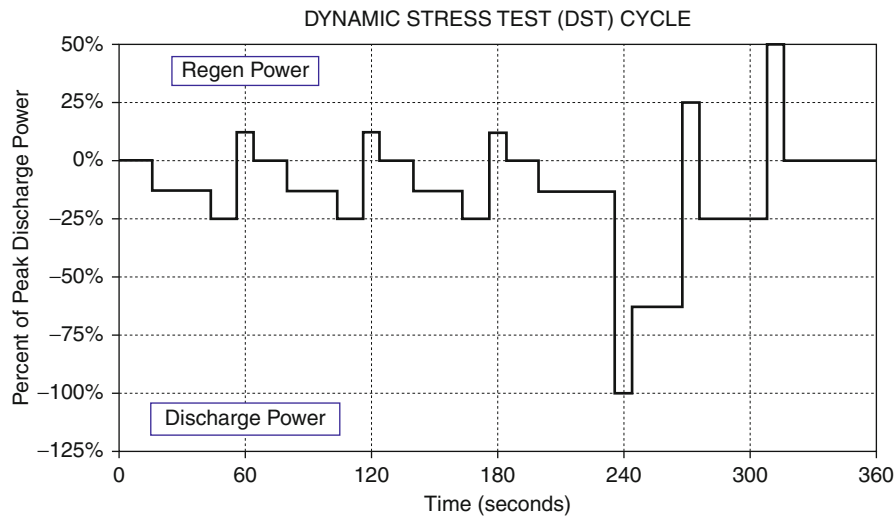
Applications that require constant current will be unable to extract the last bit of energy out the battery. Other applications, such as for EVs, have more flexibility. Some of today's EVs can operate at lower torque, which implies lower current, to allow the driver to reach a safe location before running out of battery power. Such applications can use the entire charge contained in a battery.

Although not obvious, both the graphs in Fig. 21 are related. As a cell ages, it appears to gradually lose capacity. Davide [18] explains that this capacity is actually unused, but not lost. Internal resistance of a cell increases with age, therefore the cell gets undercharged and under-discharged along the process. This issue can be resolved by allowed fixed cutoff voltages to vary internally. Due to fixed cutoff voltages, the cell charges/discharges less and less each time due to increasing internal resistance, resulting in an apparent loss of capacity. By raising the upper cutoff voltage

during charge and lowering the lower cutoff voltage during discharge, we can recover some of this lost capacity. A battery management system that is able to measure a cell's internal resistance and compensate its cutoff voltage accordingly can make better use of the cell's capacity [18].

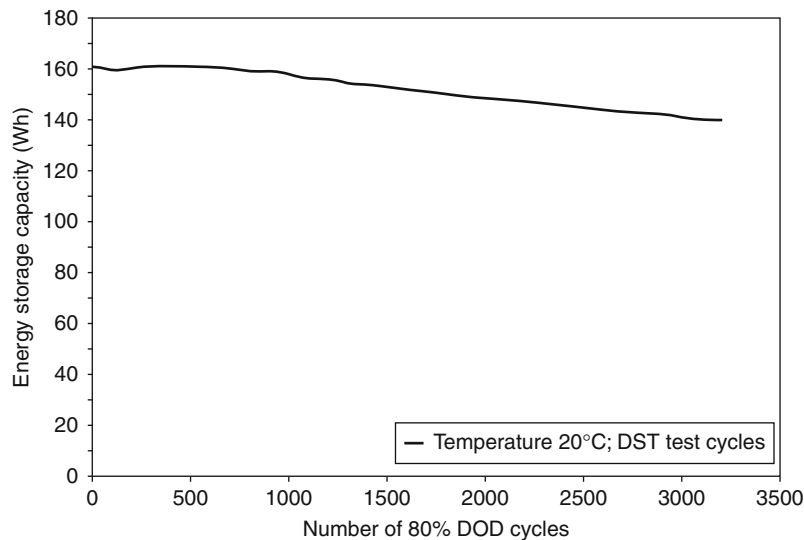
Reliability

To minimize operation and maintenance (O&M) costs for the customer, it is essential for a battery manufacturer to conduct rigorous stress tests on their battery systems. A common test adapted by manufacturers in the USA is known as the dynamic stress test (DST), developed by the United States Advanced Battery Consortium (USABC). Figure 22 shows an example of the battery charging and discharging power profiles that must be successfully followed to acquire DST conformation. The test can be performed at various temperatures to determine ideal operating conditions. The test



Battery Technologies. Figure 22

Dynamic stress test by USABC [19]



Battery Technologies. Figure 23

DST results for Saft's lithium-ion battery [20]

is designed to gauge battery performance characteristics such as partial discharge and hold, sustained climb, thermal performance, and fast charge response. One such battery was tested by the Electric Power Research Institute (EPRI). Figure 23 shows DST results of that battery, specifically energy storage capacity versus number of DST test cycles at 80% depth of discharge. As

shown, a 12.5% drop in capacity is attained after 3,000 cycles. This is in contrast to a 37% drop in capacity for NiMH batteries subject to a similar test [20]. Longer life expectancy combined with larger power density make lithium-ion batteries an ideal candidate for EVs.

Twenty watt-hours of energy storage capacity is lost after 3,000 charge–discharge cycles, as seen in Fig. 23.

Thermal Runaway

Thermal runaway (TR) is defined as a phenomenon where an increase in temperature creates conditions for further increases in temperature. Viable conditions for TR exist when a battery is producing more heat than it can dissipate. Thermal runaway can lead to leaks, venting of gas, and possibly a fire. According to Saft, temperature in a cell must be kept below 145°C to prevent conditions for TR from arising.

As battery temperature typically increases during operation, resistance of the ion-transferring electrolyte decreases. This leads to an increase in the current passing through the battery, raising the temperature of the battery even further. If the electrolyte becomes too hot, its resistance will become negligible and allow enough current to flow for chemical compounds on the cathode and anode to breakdown and short circuit.

Excessive ambient temperatures are another cause of TR, according to Saft. Computers, cell phones, and other portable devices are often subject to prolonged exposure to direct sunlight. Additionally, portable electronics could be operated in constricted spaces, with insufficient room for heat dissipation. High ambient temperatures can also harbor conditions for TR.

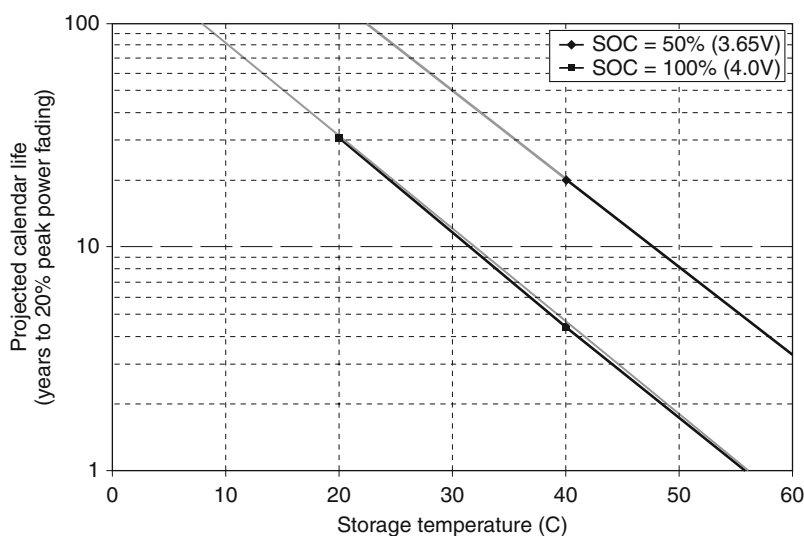
EPRI identifies overcharging as yet another source for TR [20]. Overcharging can lead to build up of lithium deposits that can penetrate the film separating

the anode and the cathode, leading to a short circuit. All lithium-based batteries are equipped with protective circuitry to avoid overcharging. Failure of protective circuitry can lead to build up of lithium-ions on the graphite anode, forming lithium dendrite. (Most metals are combined with alloys for dexterity and strength. Due to the presence of alloys, the metal tends to exist in a nonuniform, snowflake-like distribution called *dendrite*.) With increasing formation of this dendrite, useful anode surface area diminishes, leading to reduced battery capacity. If charging continues even further, the dendrite will penetrate the separator and react with the cathode, creating a short circuit. Metallic lithium is still at the developmental stage because it is prone to dendrite formation. Figure 24 depicts EPRI's projection of effects of storage temperature on battery life.

Irrespective of the cause, TR is a dangerous prospect. Potential large-scale use will require development of adequate prevention of conditions leading to TR [20]. USABC and EPRI have proposed various solutions, albeit with negative impacts on power density and capacity.

Capacity Fading

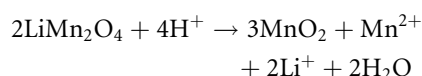
Capacity fading (CF) refers to reduction in battery capacity after repeated charge or discharge cycles.



Battery Technologies. Figure 24

Projected calendar life as a function of storage temperature [20]

Yunjian et al. [21] uses a lithium-ion battery, with lithium manganese oxide (LiMn_2O_4) as cathode and graphite as anode to study capacity fading characteristics. Lithium hexafluorophosphate (LiPF_6) is present as an electrolytic salt. The battery was charged to 4.2 V and then stored for a period of 96 h at 55°C. A notable reaction was the formulation of hydrofluoric acid (HF) and a consequent dissolution of manganese (Mn). The following reactions were noted:



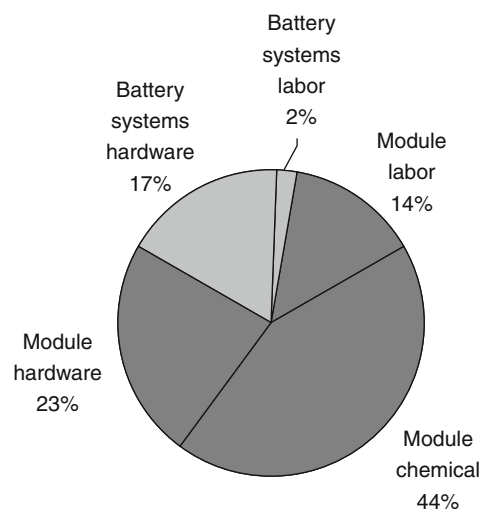
Mn^{2+} enters the electrolyte and manganese dioxide (MnO_2) is deposited on the cathode. A reported 8 mAh/g of capacity was lost on the first day. Only 2 mAh/g of capacity was lost during each of following 3 days. MnO_2 formation on the cathode protected it from engaging in further dissolution of manganese (Mn), which explains the dwindling in CF. Charge retention of the battery was found to be 83.3%, 85.8%, 86.9%, and 88.6% for those 4 days.

Elevated temperatures can accelerate the rate at which CF occurs, as evident from work done by Xia et al. [22]. When operated above 65°C, the number of operational cycles is well below the EV requirement of 1,000–1,500. Degradation of electrode materials has been found to be the main reason for CF at high temperatures [22].

Cost

Lithium-based batteries are subject to aging even if not being used. Also, lithium batteries are dependent on protective circuits to maintain safe levels of voltage and current. These factors propagate into a 40% (average) higher manufacturing cost for lithium-based batteries compared to NiMH [20]. Figure 25 provides a breakdown of costs to manufacture an EV lithium-ion battery.

Several automotive manufacturers have announced plans to incorporate lithium-based batteries for use in HEVs, although NiMH batteries currently predominate. Lithium-ion batteries store more than twice as much energy per kilogram (250–400 Wh/kg) compared to the next-best battery technology, NiMH.



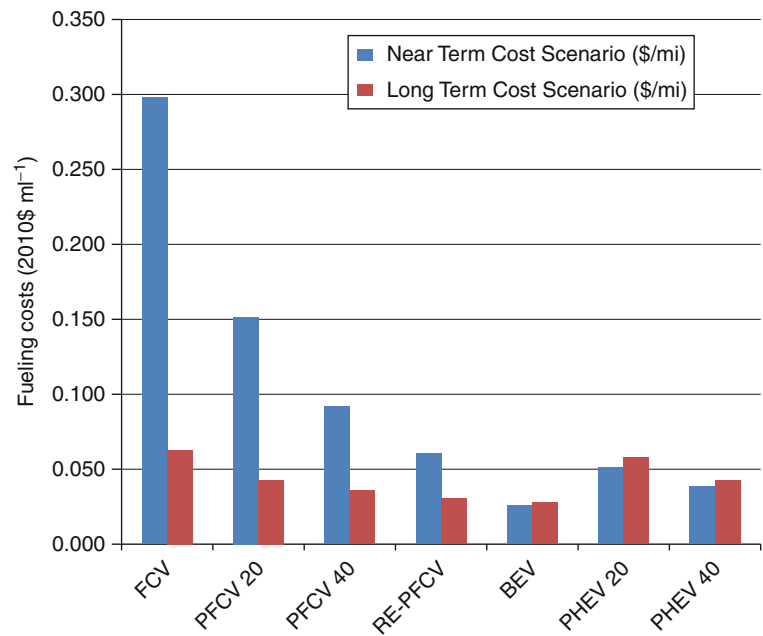
Battery Technologies. Figure 25

Component costs as percentage for Saft's EV lithium-ion battery [18]

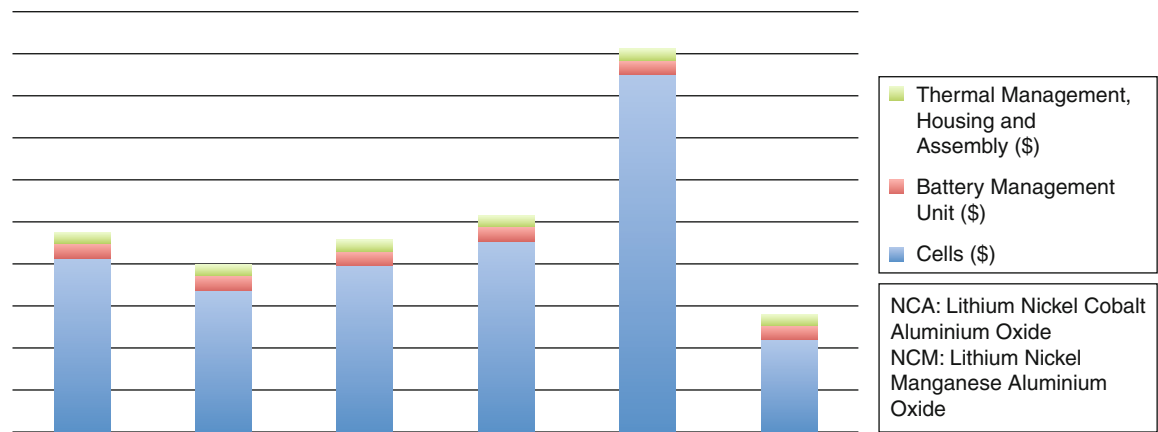
After having purchased their EV, customers are now responsible for operating costs for as long as they own the vehicle. Operating costs can vary based on battery capacity, efficiency, environmental conditions, and usage. Nevertheless, once gas savings balance out the cost of the EV, long-term savings in operating costs become apparent. A lab experiment conducted by EPRI in 2010 [23] employed various EV types, each with a lithium-ion battery system. Operating costs (loosely termed “fueling costs”) are shown in Fig. 26. Here, the following EV types were used: Fuel Cell Vehicle (FCV), Plug-in Fuel Cell Vehicle (PFCV), Range Extender Fuel Cell Vehicle (FCV), Battery Electric Vehicle (BEV), and Plug-in Hybrid Electric Vehicle (PHEV). A “20” (or “40”) in the name indicates 20 (or 40) miles on a full charge.

In the near term, FCVs are more expensive due to the cost of hydrogen. The FCV fitted with a range extender module uses considerably lesser hydrogen, as consistent with the lower near term operating cost. As expected, predominant battery use in EVs results in lower near term costs. In the long term, the difference in cost of hydrogen versus electricity became smaller, as apparent in the near identical long-term costs for all vehicle types.

To make lithium-ion batteries practical for mass-produced electric-drive vehicles, new technologies



Battery Technologies. Figure 26
Operational costs per mile for various Li-ion EV configurations [23]



Battery Technologies. Figure 27
Cost breakdown for complete battery pack used for typical PHEV40

must increase the energy the batteries store and the speed with which they can discharge it. They must also lengthen cycle life to 15 years or 241,000 km (150,000 miles) – the average life of a vehicle [24].

Perhaps it would be appropriate to compare lithium ion to other chemistries in terms of cost of a battery pack for EVs. Figure 27 provides such

a comparison for a PHEV-40, as per 2010 cost estimates made by EPRI’s Duvall et al. [23] and the Electric Auto Association.

Notably, Pb-A and NiMH (best case) appear to carry the lowest and highest overall costs respectively. It is important to mention that a typical EV lead acid battery pack only has a life of approximately

14–16 months (assuming the vehicle is driven 20–40 miles daily). On the other hand, the NiMH pack has a life span of roughly 5.5 years.

Metal–Air Batteries

Metal–air batteries get their name from their reactants which undergo electrochemical reactions to release energy. They are one of the most compact and potentially the least expensive batteries available. They are also environmentally friendly. However, their main disadvantage so far has been that electrical recharging of these batteries is very difficult and inefficient. Although many manufacturers offer units that can be refueled, where the consumed metal is mechanically replaced and processed separately, there still have not been many developers who offer rechargeable batteries. Rechargeable metal air batteries that are under production have a life of only a few hundred cycles and an efficiency of about 50% [1, 6].

Current research in lithium–air batteries have shown that they can provide an energy density of 1,700 Wh/kg, which is more than the energy density of any other battery technology present today and is comparable to the practical energy density of gasoline [6] (Fig. 28).

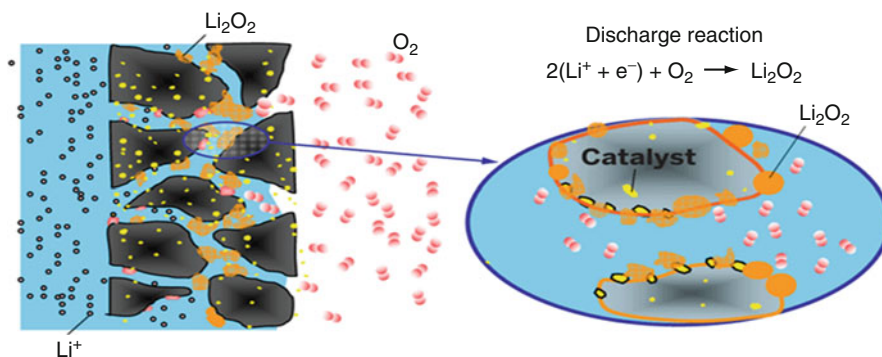
Air electrodes and metal–air battery technologies have already been used in fuel cell systems. Earlier, zinc was the predominant metal used in metal–air batteries. Recently, lithium instead of zinc as the metal has started being used which has increased the energy output eightfold. As seen in the figure above, the lithium–air battery's porous carbon cathode (gray) is flooded

with the electrolyte (blue). The Li^+ ions (small dots) react with oxygen molecules (pairs of dots) at catalyst sites (yellow) to form lithium oxides (orange). The oxygen electrode proceeding in tandem with lithium according to the reaction $2\text{Li} + \text{O}_2 \rightarrow \text{Li}_2\text{O}_2$ can deliver a capacity of 1,200 mAh/g. The first lithium–air cell was successfully assembled and discharged in 1996, but attractive rechargeability was demonstrated only recently [3].

It could be argued that such a system unites within the same device the two most prominent failures of battery and fuel-cell technologies, namely, the inability to master lithium and oxygen electrodes. These perceived issues have prevented the practical use of lithium–air batteries. Improving energy storage and preventing Li_2O_2 from clogging the electrode require a better understanding of the reaction mechanism of the oxygen electrode. Engineering and chemical advances are also required to prevent the ingress of either CO_2 or H_2O , which could react with either Li_2O_2 or lithium metal [3].

Zinc Bromine Battery

The zinc bromine battery is based on the chemical reactions between two commonly available materials, zinc and bromine. This battery was developed by Exxon in the early 1970s. It is a hybrid flow battery system since zinc is deposited on the negative electrode during the charge cycle. Unlike conventional flow batteries, the energy storage capacity of the zinc–bromine hybrid is constrained by the amount of surface area available for deposition [4, 9].



Battery Technologies. Figure 28

Li–air battery [6]

One of the main advantages of zinc–bromine batteries is that it can be fully discharged without any damage to the battery and has a life of at least 1,500 charge/discharge cycles. This battery is ideally suited in applications that require deep cycle and long cycle life energy storage. These batteries are made with low-cost, recyclable plastics and manufactured with techniques suitable for mass production and at low production costs [4].

As seen in the figure below, the battery consists of a zinc negative electrode and a bromine positive electrode separated by a microporous separator. An aqueous solution of zinc/bromide is circulated through the two compartments of the cell from two separate reservoirs. The electrolyte stream in contact with the positive electrode contains bromine which is maintained at the desired concentration by equilibrating with a bromine storage medium. The bromine storage medium is immiscible with an aqueous solution containing zinc bromide. All battery components are made from a bromine inert plastic [4] (Fig. 29).

During discharge, zinc is converted to zinc ion with the release of two electrons and bromine is converted to bromide, the zinc ion and bromine combine to form zinc bromide. The chemical process used to generate the electric current increases the zinc-ion and bromide-ion concentration in both electrolyte tanks. During charge, metallic zinc is deposited as a thin film on one

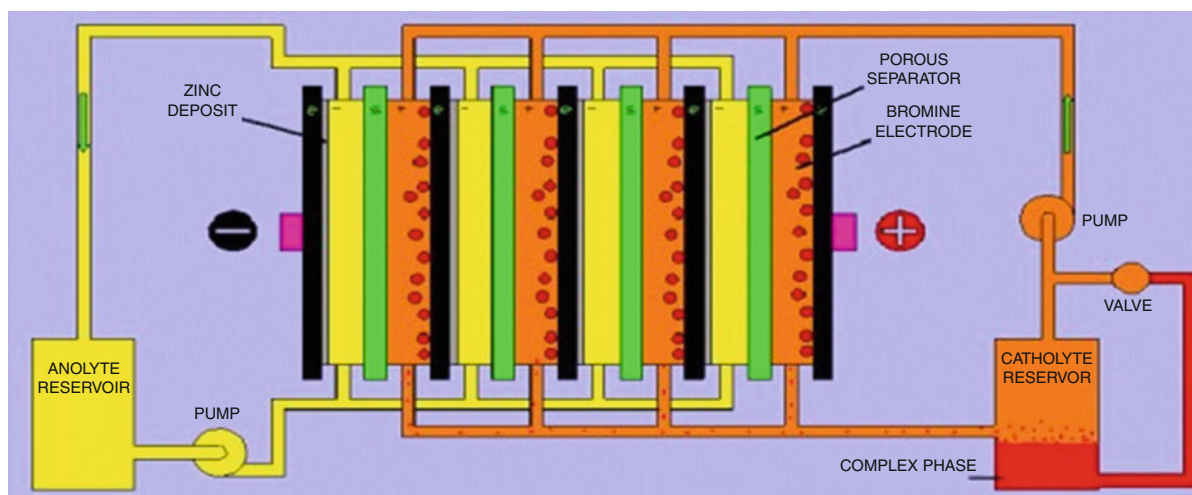
side of the plastic electrode. Meanwhile, bromine is evolved as a dilute solution on the other side of the membrane, reacting with other compounds in solution (organic amines) to form viscous, dense bromine-adduct oil that sinks to the bottom of the tank. The bromine oil is allowed to mix with the rest of the electrolyte during discharge. The net efficiency of this battery is about 75% [9].

The zinc–bromine battery uses electrodes that do not take part in the reactions but merely serve as substrates for the reactions. Therefore, there is no loss of performance, as in most rechargeable batteries, from repeated cycling causing electrode material deterioration. When the zinc–bromine battery is completely discharged all the metal zinc plated on the negative electrodes is dissolved in the electrolyte and again produced the next time the battery is charged. In the fully discharged state the zinc/bromine battery can be left indefinitely [4].

The zinc–bromine battery has an energy density of 75–85 Wh/kg. The power characteristics of the battery can be modified for selected applications, making them extremely useful for multipurpose energy storage [4].

Supercapacitors

In the field of energy storage, two parameters are fundamental for storage devices: the energy density and



Battery Technologies. Figure 29
ZnBr battery [4]

the power charging and discharging rates. The first parameter defines the amount of energy that can be stored in a given volume. The lower the maximum charging and discharging rates, the more time that is required for loading and unloading the required amount of energy into the storage device. The ideal storage device should have both a high energy density together with high power charging and discharging rates. This is unfortunately not the case and compromises have to be made. Current battery technologies have relatively high energy densities but relatively poor power densities. Supercapacitors are a compromise between batteries and conventional capacitors. Their main characteristic is that they possess both a relatively high energy density and power density [25].

Integrating with an Onboard Energy Source for an EV

The integration of the onboard energy source for an electrically propelled vehicle with a supercapacitor bank (SB) as a peak power unit can lead to substantial benefits in terms of EV performances, battery life, and energy economy. An SB made up of single cells connected in series and in parallel, featuring appropriate parameters of energy density, power density, with high charging–discharging efficiency and affordable cost can be beneficial as a suitable device to support the energy source of an electric vehicle, thus providing optimized energy management [26].

The potential benefits of an integrated system SB-electrochemical energy source are the following:

- To improve the vehicle efficiency and energy economy over variable power driving conditions
- To assure high performance and good vehicle behavioral response independently from the status of the energy source (including age)
- To improve the endurance of the energy source to the extent of its dependence on the high rate power demand
- To extend the vehicle's range at full performance as a consequence of the combined effect of load leveling of the onboard energy source and of better efficiency of energy recovery

Second to the range of the EV, high acceleration performance is a highly desired feature to achieve

integration with the majority of today's vehicles. The integration of an SB with a battery allows a system design optimized according to driving requirements, by making the specific power and specific energy parameters of the energy source independent of each other. As a consequence of this consideration, it will be possible to design the storage battery with respect to energy storage capability and life requirement without taking into account the power requirement [26].

Difference Between Capacitors and Supercapacitors

A supercapacitor differs from a conventional capacitor both in the physical phenomena and the materials from which it is made. In today's supercapacitors, the dielectric is an electrolyte interposed between two electrodes. When a voltage is applied, a double layer of charges is formed at the interface between the electrodes and the electrolyte. In the case of supercapacitors, the distance between the charges corresponds to the thickness of the double layer, that is, only a fraction of a nanometer. This accounts for the difference in terms of capacitance per square centimeter between a conventional capacitor in the (order of magnitude nF/cm^2) and a supercapacitor (order of magnitude $50,000 \text{ nF}/\text{cm}^2$) [26].

The way to increase the energy stored in a conventional capacitor is to operate at high voltages (up to 3,000 V) consistent with the dielectric breakdown voltage. In today's supercapacitors, the voltage to be applied must be limited by either the solvent or the organic electrolyte decomposition voltage (1.23 V and 3.5 V, respectively). In this case, the only way to increase the stored energy is to raise the capacitance value by adopting electrode materials with very high specific area. In particular, active carbon may reach, through suitable chemical processes, a specific area of $103 \text{ m}^2/\text{g}$, and a specific capacitance of 102 F/g . In addition, it is possible to reach very low values of the internal resistance that allows the device to provide high output power.

So far, only supercapacitors operating on the basis of charge separation phenomena due to the application of an external voltage between the electrodes have been considered. There is another type of supercapacitor, called pseudocapacitor, in which reduction and oxidation reactions occur during charge and discharge phases. The electrodes are made of metallic oxides

Battery Technologies. Table 9 Characteristics of supercapacitors based on the electrode and electrolyte material [26]

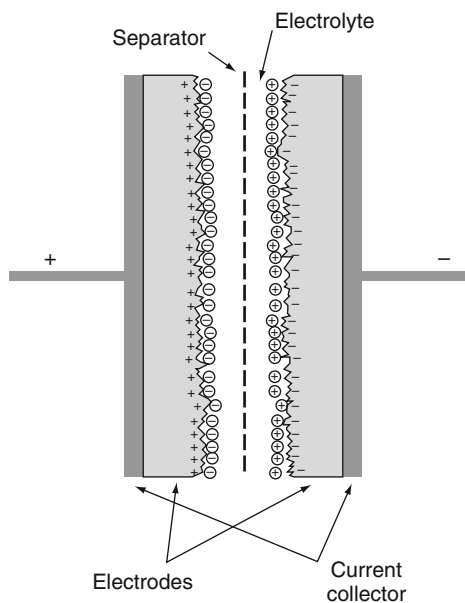
Electrode material	Carbon	Carbon	Metallic oxides
Electrolyte	Aqueous electrolyte	Organic electrolyte	Aqueous electrolyte
Maximum voltage (V)	1	3	1
Specific power (kW/kg)	0.8–2.6	1.5–5	0.5
Specific energy (Wh/kg)	0.2–1.3	3–6	1

(typically ruthenium or iridium) and electrolytes are liquid. The characteristics of supercapacitors are summarized as in Table 9 [26, 27].

Working Principle of a Supercapacitor

Supercapacitors are electrochemical double layer capacitors (EDLC). Their technology is similar to that of batteries, but the main difference is that they involve only electrostatic phenomenon (non-faradic). This is the first difference between batteries and supercapacitors. Their power density is higher because there are no chemical reactions during charging and discharging. Also, for this reason, charge storage in EDLCs is highly reversible, which allows them to achieve very high cycling stabilities. EDLCs generally operate with stable performance characteristics for many charge–discharge cycles, sometimes as many as 10^6 cycles. On the other hand, electrochemical batteries are generally limited to only about 10^3 cycles. In double-layer capacitors, the energy is stored by charge transfer at the boundary between electrode and electrolyte. The amount of stored energy is a function of the available electrode surface, the size of the ions, and the level of the electrolyte decomposition voltage [25].

Supercapacitors contain two electrodes, a separator and an electrolyte, as shown in Fig. 30. The two electrodes provide a high surface area, defining the energy density of the component. On the electrodes, current collectors with a high conducting part assure the interface between the electrodes and the connections of the supercapacitor. The two electrodes are separated by



Battery Technologies. Figure 30
Principle of supercapacitors [25]

a membrane, which allows the mobility of the charged ions and forbids electronic contact. The electrolyte supplies and conducts the ions from one electrode to the other. As the dissociation voltage of the electrolytes used is less than 3 V, this limits the maximum voltage that can be reached by the supercapacitor. Another disadvantage is lower ionic conductivity, which reduces the power capability [25].

The performance of an electrochemical double layer supercapacitor (EDLC) can be adjusted by changing the nature of its electrolyte. As mentioned earlier, an EDLC can utilize either an aqueous or organic electrolyte. Aqueous electrolytes generally have lower equivalent series resistance (ESR) compared to organic electrolytes. However, aqueous electrolytes also have lower breakdown voltages. Therefore, in choosing between an aqueous or organic electrolyte, one must consider the trade-offs between capacitance, ESR, and voltage. Because of these trade-offs, the choice of electrolyte often depends on the intended application of the supercapacitor [27].

While the nature of the electrolyte is of great importance in supercapacitor design, the subclasses of EDLCs are distinguished primarily by the form of carbon they use as an electrode material. Carbon electrode

materials generally have higher surface area, lower cost, and more established fabrication techniques than other materials such as conducting polymers and metal oxides.

Electrode Materials Used in EDLC

Activated Carbon Activated carbon is the most commonly used electrode material in EDLCs. It is less expensive and possesses a higher surface area than other carbon-based materials. Activated carbons utilize a complex porous structure composed of different sized micropores (<200 nm wide), mesopores (200–5,000 nm) and macropores (>5,000 nm) to achieve high surface areas. Although capacitance is directly proportional to surface area, evidence suggests that, for activated carbons, not all of the high surface area contributes to the capacitance of the device. This discrepancy is believed to be caused by electrolyte ions that are too large to diffuse into smaller micropores, thus preventing some pores from contributing to charge storage [27]. Research also suggests an empirical relationship between the distribution of pore sizes, energy density, and power density of the device. Larger pore sizes correlate with higher power densities and smaller pore sizes correlate with higher energy densities. As a result, the pore size distribution of activated carbon electrodes is a major area of research in EDLC design. In particular, research has been focused on determining the optimal pore size for a given ion size and upon improving the methods used to control the pore size distribution during fabrication [27].

Carbon Aerogels There is an increasing interest in using carbon aerogels as an electrode material for EDLCs. Carbon aerogels are formed from a continuous network of conductive carbon nanoparticles with interspersed mesopores. Due to their continuous structure and their ability to bond chemically to the current collector, carbon aerogels do not require the application of an additional adhesive binding agent. As a result of this, carbon aerogels have lower ESR than activated carbons. (The internal components of the capacitor (current collectors, electrodes, and electrolyte) contribute to a resistance, which is measured in aggregate by a quantity known as the equivalent series resistance (ESR). The voltage during

discharge is determined by this resistance.) The reduced ESR yields higher power and this is the primary area of interest in supercapacitor research involving carbon aerogels [27].

Carbon Nanotubes Electrodes made from this material are grown as an entangled mat of carbon nanotubes with an open and accessible network of mesopores. Unlike other carbon-based electrodes, the mesopores in carbon nanotube electrodes are interconnected, allowing a continuous charge distribution that uses almost all of the available surface area. Thus, the surface area is utilized more efficiently to achieve capacitance comparable to those in activated-carbon-based supercapacitors, even though carbon nanotube electrodes have a smaller surface area compared to activated carbon electrodes [27]. As the electrolyte ions can easily diffuse into the mesoporous network, carbon nanotube electrodes also have a lower ESR than activated carbon. In addition, several fabrication techniques have been developed to reduce the ESR even further. Carbon nanotubes can be grown directly onto the current collectors, subjected to heat-treatment or cast into colloidal suspension thin films [27]. The efficiency of the entangled mat structure allows higher energy densities [27].

Pseudocapacitors

In contrast to conventional EDLCs, which store charge electrostatically, pseudocapacitors store charge faradically through the transfer of charge between electrode and electrolyte. This is accomplished through electrosorption, reduction–oxidation reactions, and intercalation processes. These faradic processes may allow pseudocapacitors to achieve greater capacitances and energy densities than EDLCs. There are two electrode materials that are used to store charge in pseudocapacitors, conducting polymers and metal oxides [27].

Electrode Materials Used in Pseudocapacitors

Conducting Polymers Conducting polymers have a relatively high capacitance and conductivity and a relatively low ESR and cost compared to carbon-based electrode materials [27]. In particular, the *n/p*-type polymer configuration, with one negatively

charged (*n*-doped) and one positively charged (*p*-doped) conducting polymer electrode, has the greatest potential energy and power densities. However, a lack of efficient *n*-doped conducting polymer materials has prevented these pseudocapacitors from reaching their potential. Additionally, it is believed that the mechanical stress on conducting polymers during reduction–oxidation reactions limits the stability of these pseudocapacitors through many charge–discharge cycles. This reduced cycling stability has hindered the development of conducting polymer pseudocapacitors [27].

Metal Oxides Metal oxides like ruthenium oxide have high conductivity, which makes them a good electrode material for supercapacitors [27]. The capacitance of ruthenium oxide is achieved through the insertion and removal of protons into its amorphous structure. In its hydrous form, the capacitance exceeds that of carbon-based and conducting polymer materials. Furthermore, the ESR of hydrous ruthenium oxide is lower than that of other electrode materials. As a result, ruthenium oxide supercapacitors may be able to achieve higher energy and power densities than similar carbon electrode supercapacitors. However, despite this potential, the success of ruthenium oxide has been limited by its prohibitive cost. Thus, a major area of research is the development of fabrication methods and composite materials to reduce the cost of ruthenium oxide, without reducing the performance [27].

Composite Electrode Capacitors Composite electrodes integrate carbon-based materials with either conducting polymer or metal oxide materials and incorporate both physical and chemical charge storage mechanisms together in a single electrode. The carbon-based materials facilitate a capacitive double layer of charge and also provide a high-surface-area backbone that increases the contact between the deposited pseudocapacitive materials and electrolyte. The pseudocapacitive materials further increase the capacitance of the composite electrode through faradic reactions [27]. Composite electrodes constructed from carbon nanotubes and polypyrrole, a conducting polymer, have been particularly successful. This electrode is able to achieve higher capacitances than either a pure

carbon nanotube or pure polypyrrole polymer-based electrode [27]. This is attributed to the accessibility of the entangled mat structure, which allows a uniform coating of polypyrrole and a three-dimensional distribution of charge. Moreover, the structural integrity of the entangled mat limits the mechanical stress caused by the insertion and removal of ions in the deposited polypyrrole. Therefore, unlike conducting polymers, these composites have been able to achieve a cycling stability comparable to that of EDLCs having carbon-based electrodes [27].

Model for Supercapacitors

A conventional model describing the supercapacitor modeled as an equivalent electrical circuit is useful for developments of applications where supercapacitors can be used. Figure 31, below, shows such a model.

The first parameter is the capacitance of the component. It defines the capacitive behavior of the supercapacitor and the energy that can be stored. This capacitance is not constant. It is dependent on the voltage across and is the reason why the capacitance of the supercapacitor is modeled as a constant capacitor C_o , with a parallel capacitor C_v , which has a linear dependence on the voltage V [25].

$$C = C_o + C_v, \text{ where } C_v = K \bullet V \quad (3)$$

This defines the capacitance C of the component.

Following this definition, the current capacitance can be derived from (3).

$$Q = CV$$

$$I_c = dQ/dt$$

Therefore,

$$I_c = (C_o + 2K \bullet V)dV/dt \quad (4)$$

$$\text{Current capacitance } C_i = C_o + 2K \bullet V$$

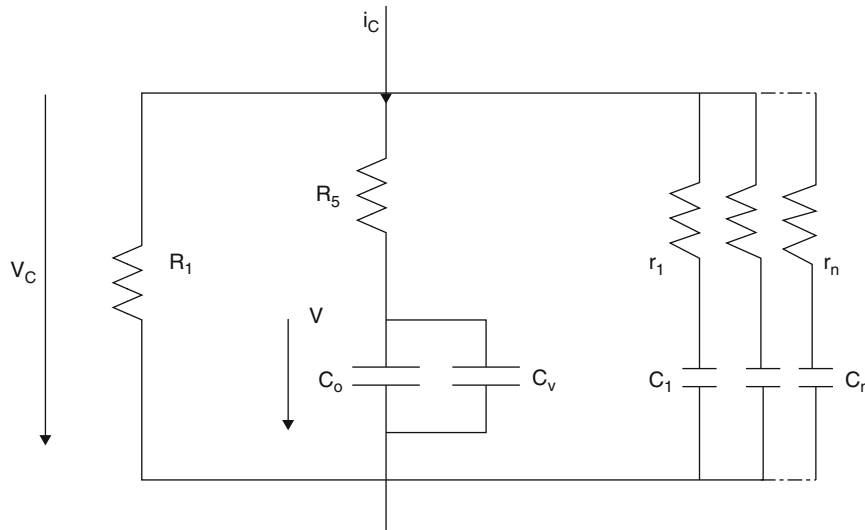
Similarly, energy capacitance can also be defined.

$$\text{Power (P)} = I_c \bullet V = (C_o + K \bullet V^2)dV/dt \quad (5)$$

$$\text{Energy (W}_w) = 1/2(C_o + 4/3(K \bullet V))V^2 \quad (6)$$

$$\text{Energy capacitance (C}_w) = C_o + 4/3(K \bullet V) \quad (7)$$

The amount of energy that can be stored into a supercapacitor can be expressed as a function of the



Battery Technologies. Figure 31

Equivalent circuit model for supercapacitors [25]

Battery Technologies. Table 10 Energy capability versus the capacitance [25]

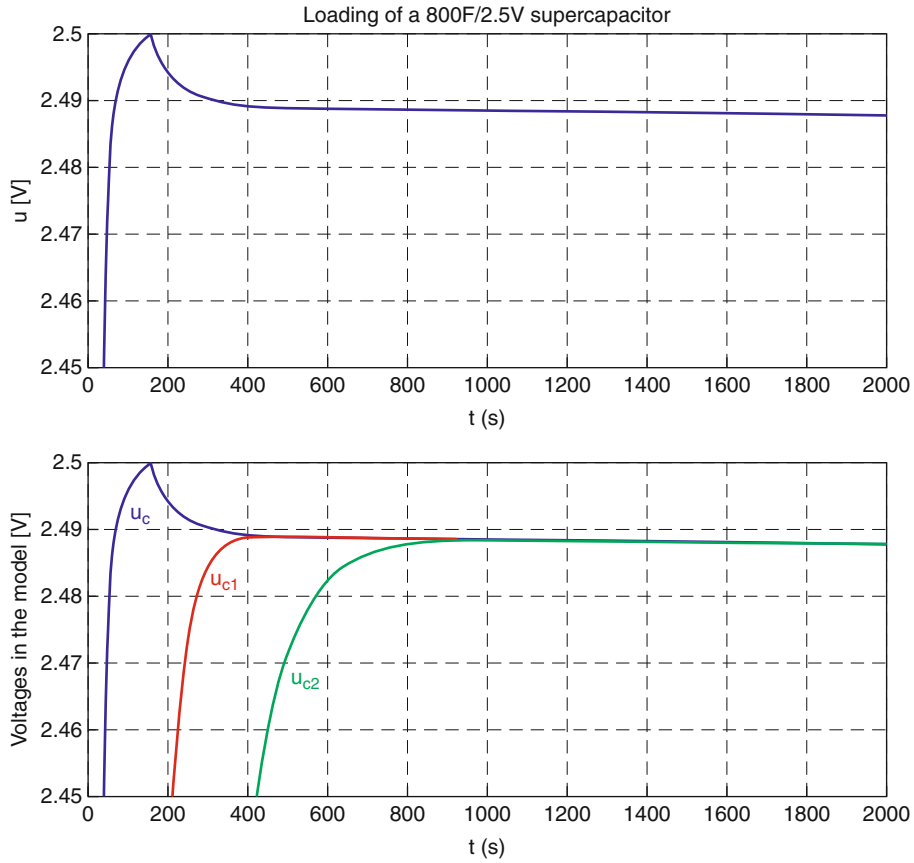
Capacitance	$C = 1,800 \text{ F}$	$W = 5,625 \text{ J}$	
Current capacitance	$C_i = 2,100 \text{ F}$	$W_i = 6,562 \text{ J}$	+16.65% increase
Energy capacitance	$C_w = 1,850 \text{ F}$	$W_w = 5,781 \text{ J}$	+2.77% increase

capacitance that is considered. This is summarized for a 1,800 F/2.5 V supercapacitor, where measurements for $C = 1,800 \text{ F}$ and $K = 150 \text{ F/V}$ in Table 10.

The current capacitance C_i shows that it is possible to store 16.55% more energy than expected considering only the constant capacitance given by the manufacturer. Another consequence of this voltage-dependent capacitance is that the voltage will not increase linearly during the charge with a constant current. Two other parameters are conventional for a supercapacitor model. The first one is the series resistor R_s that induces voltage drops during charge and discharge. Its value influences the energy efficiency of the component and its power density. The second conventional parameter is the leakage resistor R_l that induces load losses when

the component is in a standby mode. However, this resistor is not the only parameter that influences the voltage variation across a supercapacitor between a charge and discharge operation. This is illustrated in Fig. 32 [25].

The upper curve shows the typical voltage variation V_c across a 800 F/2.5 V supercapacitor during the end of its charge with a constant current. Once the charge is ended, the voltage decreases rapidly. This could be due to the leakage resistor but this is not strictly the case if the model in Fig. 31 is considered again. It makes n parallel RC circuits appear. This is illustrated in the lower part of Fig. 32 where the relaxation phenomena are presented as the charge of RC circuits with different constant times. The result is a decrease of the main voltage, not due to a dissipative component, but due to a homogenous arrangement of the loads and ions on the electrodes and in the electrolyte. Once all the voltages across all the equivalent capacitors are equal, then relaxation phenomena are supposed to be ended. The decrease of the main voltage is then linked to a leakage current. An ideal supercapacitor model should propose an infinite number of RC branches. For practical reasons linked to measurement, most of the models identify only two or three of these equivalent subcircuits [25].



Battery Technologies. Figure 32

Relaxation phenomena [25]

Sizing Method of a Supercapacitive Tank

For a supercapacitor, the total amount of energy W_M that can be stored is expressed as a conventional capacitor:

$$W_M = \frac{1}{2}(C \bullet V_M^2) \quad (8)$$

where C is the capacitance of the component and V_M is the maximum voltage. The voltage across the component has to be decreased from its maximum allowed value to 0 V for the use of the total amount of stored energy. This is not possible because the current provided by the supercapacitor should be infinite. For this reason, the minimum voltage when discharging the component has to be limited and all the energy stored in the component is not used [25]. It is then necessary to define the parameter d , which is the ratio between the minimum allowed voltage V_m for the discharging,

and the maximum voltage V_M that defines a full charging of the component. d is expressed in percent and is called the discharge voltage ratio:

$$d = (V_m/V_M) \bullet 100 \quad (9)$$

Under this condition, the usable energy W_v that a supercapacitor can provide is given by the equation:

$$W_v = W_M(1 - (d/100)^2)^2 \quad (10)$$

If $d = 50\%$, the voltage is half of the maximum voltage at the end of the discharge, then the usable energy W_v will be 75% of the total stored energy W_M . For a given usable energy, the last two equations can be combined to identify the number of supercapacitors in the supercapacitor bank.

$$N_s = 2W_v/CV_M^2(1 - (d/100)^2) \quad (11)$$

Battery Technologies. Table 11 Sizing of a supercapacitor tank

N_s	d (%)	Volume (m^3)	Weight (kg)	E (kWh)
4,872	50	1.46	1,943	7.6
5,709	60	1.71	2,283	8.92
7,164	70	2.15	2,865	11.2

Let us take an example where the supercapacitor is 1,800 F/2.5 V and the usable energy $W_u = 0.55$ MJ = 5.7 kWh. The corresponding sizing of a supercapacitive tank is given for three different values of d according to (10) and this supercapacitor in Table 11 [25].

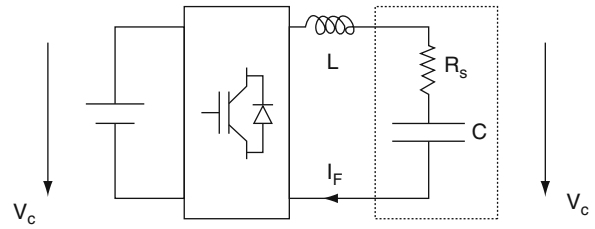
$$W_v = 0.55 \text{ MJ}, C = 1800, F_{U_M} = 2.5, V_{I_M} = 200 \text{ A}$$

The best choice should define a SB with $d = 50\%$ because of the reduced number of supercapacitors and because the usable energy W_v is 75% of the maximum stored energy W_M . On another hand, the choice of $N_s = 7,164$ ($d = 70\%$) leads to a strong oversizing of the SB where the usable energy W_v is only 51% of the maximum stored energy. This offers an interesting versatility in the management of the energy that has to be provided. If that tank and its associated power converters are designed for $d = 70\%$, it will be possible to vary the voltage more than that limit in case of stronger random power constraints [25].

Energy Efficiency and Power Availability

One of the main parameters of a supercapacitor is its series resistance. Independent of voltage falling during charge and discharge, internal losses are due to this element. Even if manufacturers succeed in reducing the value of the series resistor, its value induces an energy efficiency lower than unity with the consequence of a reduction of the power availability [25].

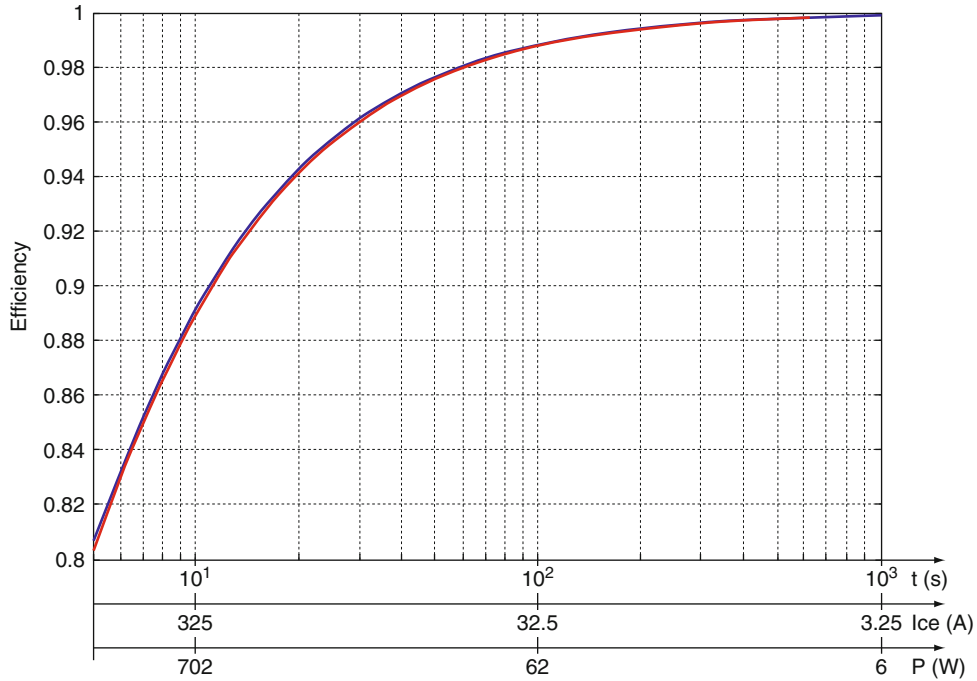
The energy efficiency of supercapacitors is taken into consideration while sizing a supercapacitive tank because the way supercapacitors are charged and discharged influence their performance. One of the only ways to control the charging/discharging process is to develop



Battery Technologies. Figure 33
Interfaces for supercapacitors [25]

power electronics interfaces in order to control the current for loading/unloading the supercapacitors [25]. This is illustrated in Fig. 33. The charge of supercapacitors is realized with a constant current, as shown in Fig. 34, where supercapacitors are loaded from a dc voltage source. The charging/discharging current is adjusted to maintain the product of $v_c I$ constant. The value of the charging/discharging current or power will define the energy efficiency of the supercapacitive tank together with the value of the equivalent series resistor. This is illustrated in Fig. 35 where the voltage discharge ratio d is 50%. In this case, 75% of the total used energy is loaded and unloaded for a 2,600 F/2.5 V/0.7 mΩ supercapacitor. The energy efficiency is presented versus the time, the current, or the power needed for loading/unloading the component [25].

The time for loading energy is chosen to be 10 s. Its energy efficiency is expected to be over 90%. This means a charging current limited to 320 A or a charging constant power limited to 700 W. The same can be applied to the current or the power during discharge. The constant power has to be kept lower than 420 W to obtain more than 90% energy efficiency. This has a consequence on the power density of the component which is 4,300 W/kg. Taking into account the energy efficiency, the power density will only be 806 W/kg if the energy efficiency is to be kept higher than 90%. This leads to an increased number of supercapacitors for the design of a storage tank. Therefore, the energy efficiency and the power availability both have to be taken into account for the design of a supercapacitor storage bank. The final parameter to be taken into account is the efficiency of the power converter needed for interfacing the supercapacitors with their load [25].



Battery Technologies. Figure 34
Charging characteristics [25]

Power Train System Architecture

Architecture conceived with the electronic interface between the SB and the traction battery are shown in Fig. 36 below.

The main characteristics of this architecture are:

- The DC-to-DC converter has to be dimensioned for the maximum power flow into and out of the SB [26].
- The SB voltage may be kept always lower than the minimum traction battery voltage. As a consequence, a simpler DC-to-DC converter design may be obtained. The DC-to-DC converter may operate only in step-up mode during the traction phase and only in step-down mode during the braking phase [26].
- A lower operating voltage implies a lower number of cells connected in series and a reduced complexity of the electronic module of the SB [26].

- The possibility to add an auxiliary generator (auxiliary power unit) configuration without modifying the existing structure [26].

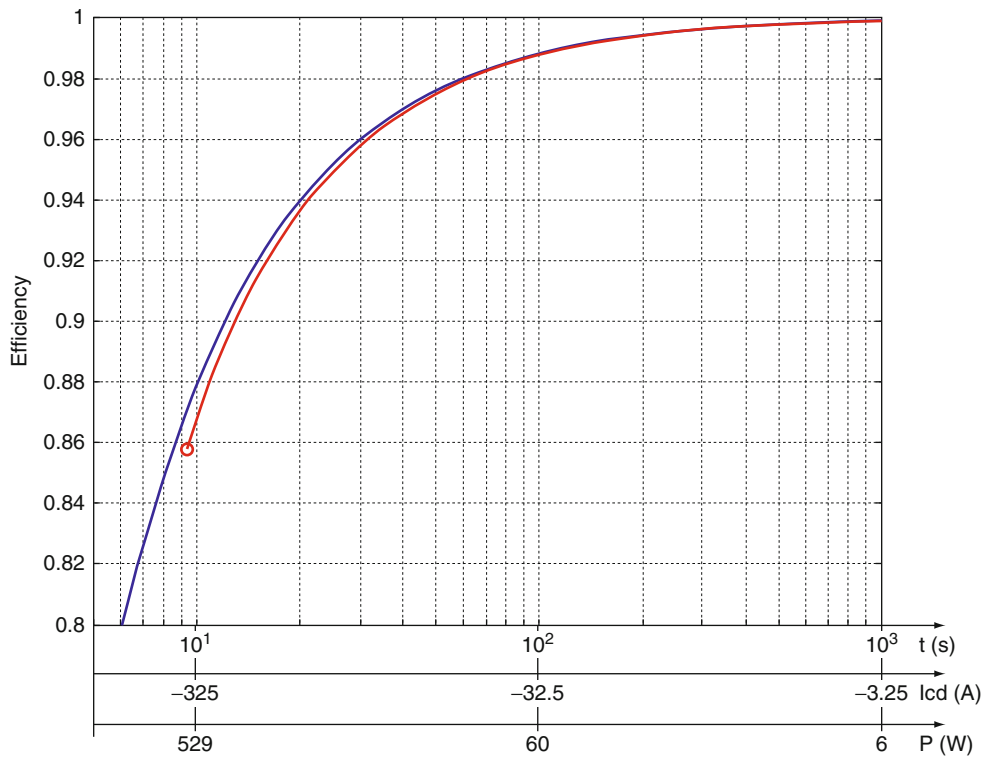
Future Developments in Supercapacitors

Currently, there is work in progress on the development of supercapacitors using solid dielectrics.

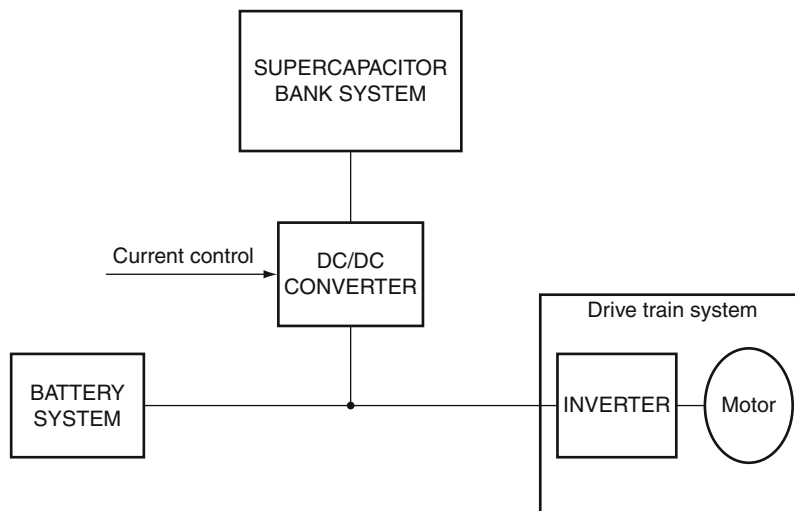
The energy density stored in a capacitor is given by:

$$W = \frac{1}{2} \epsilon_o \epsilon_r E^2$$

ϵ_o is the dielectric constant of free space, ϵ_r is the relative dielectric constant, and E is the electric field strength. Relative dielectric constants of 200,000 have been measured for 500 nm particles of BaTiO₃ coated with 5 nm of SiO₂ [28]. If these particles can be fabricated into supercapacitors with breakdown electric field strengths of the order of the breakdown strength of SiO₂, around 6×10^6 V/cm, then energy densities of the order of



Battery Technologies. Figure 35
Discharging characteristics [25]



Battery Technologies. Figure 36
Powertrain architecture with DC/DC converter and series supercapacitor bank series connected [26]

Battery Technologies. Table 12 Recommendations for future work

Action	Short term	2011–2013	2012–2016	2015–2020
Develop value propositions for storage to enable more renewable integration	Conduct assessment of utility and private renewable integration	Simulation and cost-benefit analysis of renewable plants and private systems	Large-scale demonstrations	Value and risk of renewable integration verified by the utility and understood by the end user
Development and enforcement of regulations	Develop target for development of regulations to address issues and risks associated with storage systems	Persistent enforcement of regulations in all types of regions (high and low renewable concentration)	Monitor progress of regulations and provide feedback for improvement in methodologies of local utility	Identification and continued enforcement of key regulations
Scenario modeling	Develop models for accurate forecasting of resource accessibility, demand, dispatch capabilities, pricing, and reliability	Identify incremental (smart grid, nuclear) and detrimental (EV, storage) technologies, in terms of grid operational risk	Demonstration of effects of best- and worst-case scenarios on supply/demand, technological development, and capital costs	Identification of relevant scenarios that will help guide the future development of potential storage technologies
Contribution: utility and public	Development of customer and utility actions for propagation of the renewable agenda	Assessment and regulated enforcement of utility enforced actions (e.g., price incentive for customers, storage management)	Assessment of potential customer actions (e.g., use of energy efficient devices)	Identification of low-risk actions for the utility and the customer
Reliability assessment	Develop current, short- and long-term assessment roadmap for risks associated with storage integration	Identify key factors affecting reliability of storage systems (e.g., variability, ramping requirements, peak mismatch)	Develop plan to proportionally increase integration of low-risk storage systems, with increasing demand, to achieve higher base-load penetration	Studious development of reliability risks and solutions for potential storage technologies

100 KJ/cm³ may be possible. If very high energy densities are achieved, these supercapacitors may replace batteries in EVs. There are a variety of materials with which very high dielectric constants can be obtained but there is a great deal of work to be done before these supercapacitors become available for EVs [28].

Recommendations for Future Work

Various applications and options discussed in this entry are still in the development phase

and therefore are not “grid-ready.” Current progress in the energy storage sector is limited to fulfillment of functional specifications only. Grid storage solutions are a long term goal for this sector. To develop these solutions, short-term goals need to include fundamental research, analysis, testing, evaluation of risk, and demonstration of technology. Table 12 is considered a starting point for the fulfillment of short- and long-term goals.

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Bicycle Integration with Public Transport

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Article Outline

Glossary

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Introduction

Trends in Bike-Transit Integration

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Case Studies of Bike-Transit Integration

Future Directions

Bibliography

Glossary

Bike lane A special road lane reserved for bikes only, usually about 4–6 ft wide, normally located on the right-hand side of the road.

Bike locker A box-like metal or plastic container for secure bike storage, often at rail stations, usually rented on a monthly basis.

Bike rack A device on which bikes can be mounted for transport (on buses) or attached for storage and security (on sidewalks).

Bike station Full-service, secure bike parking facility, usually providing repair and rental services, accessories, and touring advice.

Bus Motorized coach services providing communal transport on roads, usually in mixed traffic, but sometimes as part of special bus rapid transit (BRT) systems with separate rights of way.

Light rail Type of rail system similar to streetcars (trams) but often with separate right of way over at least part of its route, special boarding stations, and pre-paid fares.

Metro Urban rail system with separate rights of way, frequent service, and high carrying capacity, usually found only in large cities.

Public transport/transit General term for communal transport in cities, including buses, trams, trolleys, light rail, metros, suburban rail, ferries, and funiculars.

Suburban rail Short-distance passenger rail systems connecting large cities with their surrounding metropolitan areas, with longer distances between stops and less frequent service than metro systems.

Definition of the Subject and Its Importance

Coordinating bicycling with public transport is mutually beneficial, enhancing the benefits of both modes and encouraging more bicycling as well as more public transport use. Bicycling supports public transport by extending the catchment area of transit stops far beyond walking range and at much lower cost than neighborhood feeder buses and park-and-ride facilities for cars. Access to public transport helps cyclists make longer trips than possible by bike. Transit services can also provide convenient alternatives when cyclists encounter bad weather, difficult topography, gaps in the bikeway network, and mechanical failures.

Introduction

The overall importance of both bicycling and public transport in northern Europe has provided a strong rationale for coordinating these two modes of urban transport in recent decades [1]. European studies find that coordinating bicycling with public transport is mutually beneficial, enhancing the benefits of both modes and encouraging more bicycling as well as more public transport use [2–8]. In the Netherlands, 35% of all rail passengers reach their stations by bike – compared to 25% in Denmark and 9% in Sweden [1].

The main form of bike-transit integration in Europe is bike parking at suburban train and metro stations [1]. In the Netherlands, there are 350,000 bike parking spaces at train stations. German cities also have extensive bike parking at rail stations. The City of Berlin, for example, has over 32,000 bike parking spaces at its metro and suburban rail stations [9]. By comparison, no city in North America has more than 15,000 bike parking spaces of any kind, let alone at public transport stops.

The most impressive bike-and-ride facilities in Europe are state-of-the-art “bike stations,” which

provide secure, sheltered parking as well as a wide range of services such as bike repairs, accessories, washing, rentals, and travel advice. In 2007, there were 67 bike stations in the Netherlands, 70 in Germany, and 20 in Switzerland, almost always located adjacent to train stations to facilitate bike-and-ride [1, 5, 10–12]. As noted later in this entry, there are only ten bike stations in all of North America, and they are much smaller than those in Europe.

North America obviously lags behind Europe in the integration of bicycling and public transport. In the past, bike-and-ride in North America was limited by low overall levels of cycling and public transport use in most cities, just the reverse of the situation in northern Europe [1, 5, 12, 13]. In recent years, however, both cycling levels and public transport use have risen sharply in the USA and Canada, and bike-and-ride trips have been increasing as well. Indeed, in some cities it has been so successful that the demand for bike-and-ride facilities exceeds the available supply [14, 15].

This entry describes the programs and policies currently being implemented in North America to integrate bicycling with public transport. It starts off with a brief overview of the various kinds of integration and the extent of their implementation. Most of the entry, however, is devoted to case studies of bike-transit integration in two large cities in Canada (Toronto and Vancouver) and six large cities in the USA (San Francisco, Portland, Minneapolis, Chicago, Washington, DC, and New York City). The case study analysis compares the type and extent of integration measures undertaken in the various cities, noting the strengths and weaknesses of each city's integration policies. The entry concludes by identifying the most innovative and successful policies in the eight cities and offers policy recommendations for future improvements.

Trends in Bike-Transit Integration

In recent years, levels of cycling and public transport use have reached record highs in both the USA and Canada. In 2008 public transport use in the USA was at its highest level since the early 1960s [16, 17]. Between 1995 and 2008, public transport trips rose by 38% in the USA and by 46% in Canada [17, 18]. Similarly, levels of cycling have increased considerably since

1990. In the USA the total number of bike trips to work increased by 32% from 1990 to 2005–2007 (averaged) [19, 20]. Over the shorter period 1996–2006, the number of bike trips to work in Canada rose by an even larger 42% [21].

While rising public transport use and increased cycling have provided the rationale for more bike-transit integration, federal funding in the USA has provided the necessary financing for a wide range of projects implemented in recent years at the state and local government levels [14, 15, 22, 23]. Indeed, the federal government finances some categories of bike-transit integration projects with an especially high 95% federal share. The integration of public transport with cycling has been endorsed by the Federal Transit Administration, the Federal Highway Administration, and the Transportation Research Board [14, 15, 24]. The Transport Association of Canada [25] and Transport Canada [26] have also endorsed bike-transit integration, but there is no federal funding for urban transport in Canada. There is no federal funding for urban transport in Canada, but provincial and local governments have provided large increases in funding for public transport and bicycling in recent years, including projects aimed at better integration [27, 28].

As documented in this entry, virtually every large city in the USA and Canada has been undertaking a range of measures to promote bike-and-ride. There are five main categories of measures to promote bike-transit integration:

- (a) Provision of bike parking at rail stations and bus stops, with different degrees of shelter and security
- (b) Multifunctional bike stations providing not only parking but also a range of services such as bike rentals, repairs, parts and accessories, bike washing, showers and lockers, and touring advice
- (c) Bike racks on buses, usually exterior, but occasionally interior storage
- (d) Bikes on board vehicles, usually rail vehicles, sometimes with special bike racks, hooks, or even bike cars on trains
- (e) Bike paths, lanes, and on-street routes that lead to public transport stations and stops, thus facilitating the bike's role as feeders and collectors for public transport

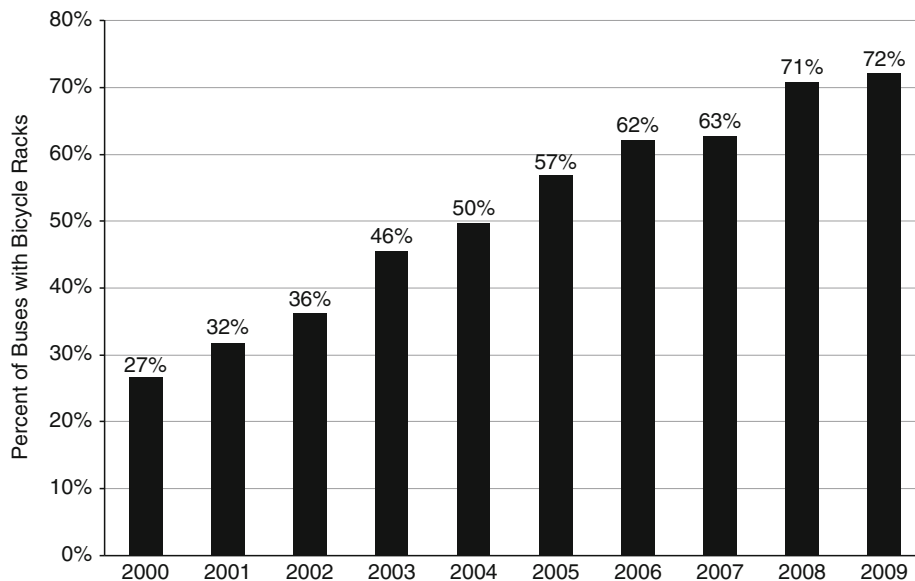
Extent of Bike-and-Ride Facilities in North America

The only available national statistics on bike parking at public transport stops are from recent surveys of 272 American and Canadian transit systems by the American Public Transportation Association [29, 30]. In the USA, the supply of bike parking spaces in 2008 was 24,178 at rail stations, 9,005 at bus stops, and 176 at ferry terminals. For the same year, Canadian systems reported 2,892 bike parking spaces at rail stations and 481 at bus stops. Between 2006 and 2008, the supply of bike parking increased by 67% in Canada and 26% in the USA [29, 30]. That is impressive progress, but it is striking that in 2008, the total supply of bike parking at public transport systems in the entire USA was only slightly more than the 32,000 spaces in Berlin, Germany [9].

Not only is there much less bike parking in North America, but it is far less likely to be sheltered and/or guarded. Throughout northern Europe, there has been a trend toward sheltered, guarded bike parking, usually outdoors but increasingly in bike stations [1, 5, 9, 12, 31, 32]. By comparison, unattended bike lockers are the main form of secure bike parking at North American public transport stops. Of the 56 large American and

Canadian transit systems surveyed by the Transportation Research Board [15], 14 systems provided bike lockers at some of their rail and bus stops, but the actual number of lockers was not reported. The same TRB survey reported eight staffed bike parking stations in 2005, mainly on the West Coast. A few more bike stations have opened since then [10].

By far the most important form of bike-transit integration in North America is bike racks on buses. Indeed, on this dimension, North America is far ahead of Europe, where very few buses come equipped with bike racks. That is not surprising since 60% of all public transport trips in the USA are by bus [18]. Bike racks are inexpensive to install, easy to operate, and do not take up space on the vehicles themselves [15]. The 2005 TRB survey found that systems throughout the USA and Canada provide bike racks on buses, and that most systems have eliminated fees they had previously charged for rack use. As shown in Fig. 1, the percentage of buses with bike racks almost tripled in the USA in only 8 years, from 27% in 2000 to 72% in 2009 [30, 33]. Since 60% of all public transport trips in the USA are by bus, it is understandable that the focus of bike-transit integration efforts in North America has been on bus-bike racks [18, 33]. They are inexpensive to install, easy



Bicycle Integration with Public Transport. Figure 1

Trend in percentage of buses with exterior bicycle racks in the USA, 2001–2009 [18]

to operate, and do not take up space on the vehicles themselves [15].

Another important form of bike-transit integration is the permission to take bikes on board public transport vehicles, since that enables cyclists to ride their bikes to and from public transport stops at both ends of their trips. Few public transport systems permit bikes to be taken on board buses unless they are compact, folding bikes. But most systems permit bikes on light rail, metro, and suburban rail trains, except during peak hour periods when crowding makes this infeasible [15]. Moreover, an increasing number of public transport systems are providing special accommodations for bikes on trains, such as bike racks, bike hooks, special bike holding areas near the doors, and even special bike cars – although rarely [15, 33].

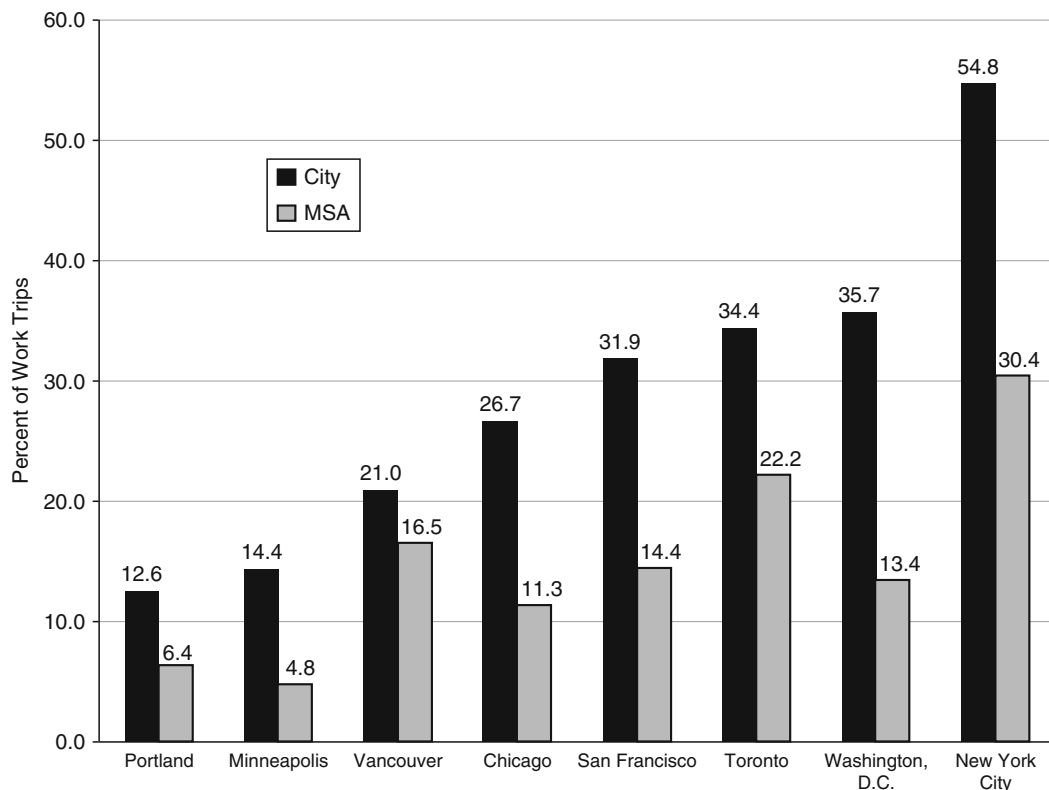
The last aspect of bike-transit integration is the coordination of bike routes with public transport stops. There are no national statistics available on the extent of implementation, and it would be hard to

quantify at any rate. Nevertheless, the eight case studies qualitatively assess this aspect of bike-transit integration in each of the cities.

Case Studies of Bike-Transit Integration

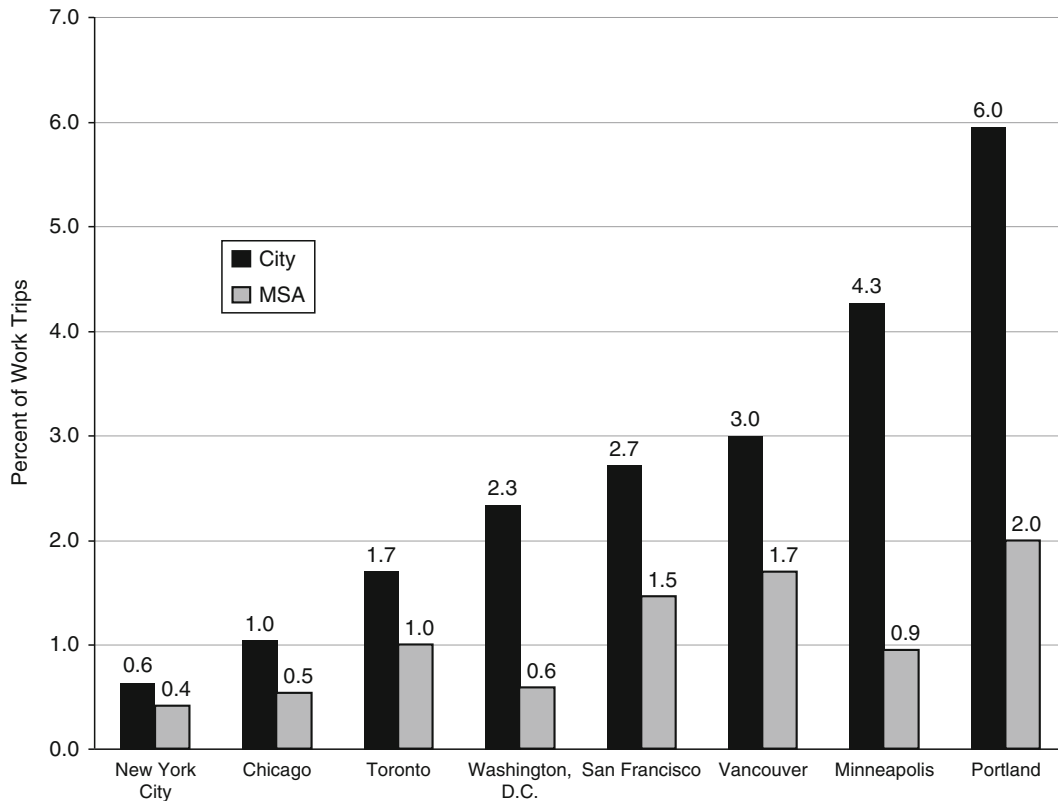
All eight of the case study cities are large, but they vary considerably in metropolitan area population, ranging from 2.2 million in Portland, Oregon, to 18.2 million in New York City. The cities also vary widely in their geographic locations, climate, and topography. Most important for this study, they vary greatly in the share of trips covered by bicycling and public transport, as shown in Figs. 2 and 3.

In 2006, public transport shares of work trips for central city residents ranged from only 13% in Portland to 55% in New York (Fig. 2). Public transport trip shares for metropolitan areas ranged from 5% in Minneapolis to 30% in New York. The Canadian cities of Vancouver and Toronto have relatively high public



Bicycle Integration with Public Transport. Figure 2

Public transportation share of work trips in US and Canadian cities and metropolitan areas, 2006/2008 [20, 34]



Bicycle Integration with Public Transport. Figure 3

Bicycling share of work trips in US and Canadian cities and metropolitan areas, 2006/2008 [20, 34]

transport use for their intermediate size. Indeed, their metropolitan areas have higher public transport mode shares than the Chicago area. Other studies confirm that, controlling for population size, Canadian cities have slightly more than twice as many public transport trips per capita as American cities [35, 36]. Without exception, public transport use is higher in all eight central cities than in their suburbs. The difference is far smaller in Toronto and Vancouver than for the American cities, because of the higher density of Canadian suburbs as well as the greater provision of public transport services there [35, 36].

Levels of cycling also vary greatly among the eight cities (Fig. 3). Portland (6.0%) and Minneapolis (4.3%) had the highest bike mode shares of work trips in 2006, but Vancouver (3.0%) and San Francisco (2.7%) were not far behind. By comparison, cycling to work in New York (0.6%) and Chicago (1.0%) is rare. Similar to levels of public transport use, bicycling is

much higher in central cities than in the suburbs. The differences for Canadian cities, however, tend to be smaller than for American cities, and the reason, again, is the much higher density of Canadian suburbs vis-à-vis American suburbs [28].

There are no comparable statistics on levels of bike-and-ride in each of these cities, since the most recent American and Canadian national travel surveys only report the main mode of transport for the work trip. Figures 2 and 3 provide useful background, however, by portraying the overall levels of cycling and public transport in the eight cities and their corresponding metropolitan areas. On the basis of European experience, it would seem that the higher the levels of both cycling and public transport use, the greater the potential for bike-transit coordination. On the other hand, where there are large imbalances between the two modes, it might suggest that the modes substitute for each other rather than complement each other. For example, the

extremely low level of cycling in New York might be partly due to a high level of public transport use. Conversely, Portland and Minneapolis, the cities with the highest bike mode shares, have the lowest public transport mode shares, suggesting that some bike trips might substitute for public transport trips. There are many possible explanations for the different levels of cycling and public transport use, but a detailed analysis is beyond the scope of this entry, which is limited to the more modest goal of examining the nature and extent of bike-and-ride programs in these eight case-study cities [1, 4, 5, 7].

Efforts to integrate cycling with public transport vary greatly among the eight case studies. New York City, for example, has done little to promote bike-and-ride, while San Francisco, Vancouver, and Portland have implemented the entire gamut of integration measures. The following section highlights the most important aspects of bike-and-ride policies in each city, noting in particular the strengths and weaknesses of current policies.

Unless otherwise indicated, the information for these case studies was obtained by the authors directly from bicycling planners, public transport systems, metropolitan planning organizations, city transport departments, and nongovernmental cycling and sustainable transport organizations in each metropolitan area. The same panel of transit and cycling experts also reviewed the case studies of their cities at several stages to check for accuracy, consistency, and completeness.

San Francisco

The San Francisco Bay Area has been a leader in bike-transit integration efforts in North America. Its regional metro system Bay Area Rapid Transit (BART) provides bike parking at almost all 43 stations, with a total of 4,313 bike parking spaces in 2009, including 1,010 in secure bike lockers. In order to increase convenience and flexibility, BART has been introducing electronic bike lockers (294 as of 2009), which are available on a first-come, first-serve basis and do not require advance subscriptions. Caltrain, the suburban rail line from San Francisco south to Palo Alto and San Jose, provides bike parking at all 32 stations, with a total of 1,100 bike lockers and 400 bike racks.

The San Francisco Bay Area had five of the ten bike stations in the USA in 2009: 226 bike parking spaces at two Caltrain stations and 433 spaces at three BART stations. The BART and SF Caltrain Bike Stations provide free, attended bicycle parking, while the Palo Alto facility is an unattended, fee-based garage. Utilization rates of the bike stations vary widely, from over 100% at the Berkeley BART station to only 11% at the Palo Alto Caltrain station. BART will soon triple the size of the Berkeley bike station and move it above ground to increase accessibility.

Cyclists prefer to take bikes on board, however. A 2008 survey found that 72% of bike-and-ride passengers carried their bikes with them, compared to only 28% who parked them at BART stations. Bikes are allowed on BART trains except during peak hours in the peak direction. Although Caltrain has no time restrictions, cyclists are often denied boarding on rush hour trains because all bike spaces are already occupied. Neither BART nor Caltrain charge a fee for bringing bikes on board. Moreover, Caltrain's lead cars provide special accommodations for 16–32 bikes, depending on time of day and direction of travel. Most of the numerous ferry lines in the Bay Area also permit bikes on board with no extra fee. Folding bikes are allowed on BART and Caltrain at all times, but are not permitted on board San Francisco's MUNI buses, streetcars, cable cars, and light rail vehicles. Complementing bike access to BART and Caltrain services, virtually all buses of all public transport systems in the San Francisco Bay Area are equipped with bike racks, free of charge to cyclists.

There is limited coordination of bike routes with public transport routes. To avoid bus-bike conflicts, bike routes are not usually located on bus routes in San Francisco, but are on parallel streets. Due to the extensive and fine-grained network of bus and rail routes in San Francisco, bike routes often lead to public transport stops, even without any explicit coordination. The Regional Bicycle Plan as well as the Bike Plans of BART and Caltrain explicitly encourage coordination of bike routes and facilities with public transport. Outside of San Francisco, where public transport routes and stations are farther apart, many communities make an explicit effort to coordinate bike routes with key stops.

Overall, bike-transit integration efforts in the San Francisco Bay Area have been successful.

The percentage of public transport trips combined with cycling has more than tripled since 1990. Nevertheless, several problems remain. For example, it is difficult for cyclists to get across the San Francisco Bay during rush hours, since bikes are prohibited from BART trains in peak directions and not permitted on the Bay Bridge. Similarly, Caltrain has problems accommodating bikes on board in the peak hour and often denies boarding to cyclists. The exclusion of bikes from Muni's light rail lines is also a problem for cyclists. Overall, however, the available evidence suggests that bike-transit integration efforts have been successful.

Portland

As shown in Fig. 2, Portland has the highest bike share of work trips of any large American city (6.0%). Thus, one would expect a high degree of bike-transit coordination. Bike-and-ride in Portland, however, is quite different from that in San Francisco and mainly involves bikes on transit vehicles. TriMet, Portland's public transport system, estimates that ten times more bikes are taken on their LRT vehicles than parked at LRT stations (2,100 vs. 200 per weekday). There are no fees, no permit requirements, and no time of day or directional restrictions for taking bikes on LRT vehicles. Every train has a low-floor car especially designed to facilitate bike access, with waiting areas and four bike hooks located near the doors. But passengers without bikes have priority to board crowded trains. All buses in the Portland area have bike racks, another inducement for cyclists to ride with their bikes instead of parking them.

By comparison, Portland does not provide much bike parking at train and bus stops. In 2009, there were a total of 670 bike parking spaces at TriMet LRT stops and transit centers (major transfer hubs for several bus or LRT lines). Of those, almost half were bike lockers. In addition, there were city-owned bike lockers at 15 locations in downtown Portland, most of which are near bus or rail services. In sharp contrast to San Francisco, Portland does not have any bike stations, which is surprising given its high bike mode share and wide range of other pro-bike policies and programs. Bicycling planners and public transport officials in Portland plan to improve bike parking at transit stops by installing 196 bike lockers and 168 bike racks at LRT extensions.

Portland cyclists prefer taking their bikes on board transit vehicles. A survey by TriMet indicated that 76% of cyclists would not be willing to park their bikes at a transit stop even if there were sheltered and secure bike parking available. The advantage of taking bikes on buses or rail vehicles is that bikes can then be used at both ends of the transit trip. So the aversion to parking bikes at bus and rail stops may be due more to convenience than to concerns over theft or vandalism.

Portland carefully and explicitly coordinates its bikeway network with its public transport network. The city has set the goal of a seamless link between cycling and transit. Bike routes are designed to facilitate access to public transport stops. Most transit centers are served by multiple bikeways. Moreover, city planners give special consideration to enhancing bike access to transit stops in outlying areas too far away from the city center for most people to cover by bike alone. Nevertheless, as in most cities, there are some public transport stops that are difficult or dangerous to access by bike. As the largest of America's three platinum level Bicycling Friendly Communities, Portland has already made impressive progress at integrating cycling with public transport and seems sure to continue on that path.

Vancouver

Similar to San Francisco and Portland, Vancouver has vigorously promoted the integration of public transport and cycling. The unique advantage in Metro Vancouver is TransLink, the fully integrated, multimodal regional transportation authority. Unlike the other case studies, public transport, major roadways, and bicycling in Vancouver are all handled within the same agency. The coordination of cycling and public transport is obvious and natural in such a multimodal agency – as reflected in TransLink's plans, funding, construction projects, vehicle procurement, and operating procedures. Over the past 10 years, TransLink has spent over \$12 million specifically on bike-transit integration.

As in the San Francisco and Portland areas, all buses in Metro Vancouver are equipped with bike racks. Similar to San Francisco's BART, bikes are allowed on Vancouver's SkyTrain except during peak hours in the peak direction due to problems of overcrowding. Until recently, there were no special accommodations for

bikes on SkyTrains, but all future vehicles will provide a special area for bikes in the rear of each car with a leaning rail and fold-up seats. Bikes are allowed at all times on West Coast Express trains for a \$.50 charge. SeaBus ferries permit bikes on board at all times without charge. Almost all of TransLink's rail and ferry services are fully accessible – through elevators, ramps, or level boarding – thus facilitating bike-and-ride.

There are bike racks at all SkyTrain and West Coast Express rail stations as well as park-and-ride lots and transit nodes with interchanges of several bus or rail lines. In 2008, Vancouver had a total of 1,060 parking spaces at transit stops: 660 spaces in racks and 400 secure bike lockers. TransLink plans to increase the overall supply of bike parking at transit stops in the coming years, with a special focus on improving the quality of bike parking, especially secure short-term bike parking. Bike stations at the most important transit hubs are also being considered.

Thanks to its multimodal orientation, TransLink explicitly coordinates bike routes with public transport. For example, the construction of the Millennium, Expo, and Canada SkyTrain lines included traffic-protected, parallel bike routes to foster bicyclist access to public transport. Another aspect of TransLink's multimodalism is the focused promotion of cycling in central corridors where bus and rail vehicles are the most crowded, and where cycling has the potential to divert some of the overload and thus reduce crowding. That coordination of demand and supply between the two modes is rare and emphasizes the advantages of multi-modal agencies such as TransLink.

Minneapolis

Although Minneapolis is, by far, the coldest of the eight cities, it has the second highest bike share of work trips after Portland (4.3% vs. 6.0%). Public transport's share of work trips is slightly higher in Minneapolis than in Portland (13.4% vs. 11.2%), but much lower than in any of the other cities (Fig. 2).

Metro Transit had 497 bike parking spaces at its light rail and bus stops in 2007: 271 spaces in bike racks and 226 bike lockers. Minneapolis has a staffed bike station, the Midtown Bike Center, with 100 bike parking spaces, repairs, rentals, and a café. It is only

a block from the Chicago and Lake Streets transit hub, which serves two of the city's busiest bus lines. Perhaps the city's most ingenious policy is the official designation of 35,000 traffic sign posts as bike parking with 70,000 bike parking spaces, assuming two bikes parked at each post. The city also considers that a form of bike-transit integration, since many traffic sign posts are near bus stops, including the bus stop post itself.

All Metro Transit and suburban transit buses are equipped with exterior bike racks, and the city has five stationary bike racks for first-time users to practice loading their bikes. Every light rail vehicle has interior vertical racks that accommodate four bikes. Bike-and-ride has become increasingly popular in Minneapolis. Metro Transit surveys in spring 2007 and fall 2008 found a doubling in the number of bicycles transported on bus racks and a 41% increase in bikes on light rail. On an average weekday in 2008 Metro Transit buses carried 870 bikes. Only 4% of cyclists had to wait for another bus due to racks being filled.

There is no explicit policy of coordinating bike routes and transit stops in Minneapolis, and city officials emphasize the need to improve cycling facilities feeding into public transport stops. Some bike routes already lead to transit stops or parallel transit lines. For example, the Hiawatha LRT line runs parallel to an off-street bike path for most of its length in Minneapolis, thus providing an alternative for cyclists on that route.

Chicago

With the second largest transit system in the USA, Chicago has made impressive efforts to integrate cycling with public transport. Its special distinction lies in the innovative provision of bike parking at rail stations, tailoring the design of parking facilities to each station's particular situation. With 6,420 parking spaces at its rail stations, Chicago has about the same amount of bike-and-ride parking as the San Francisco Bay Area, and far more than other cities in North America.

There are 2,153 bike parking spaces at 131 of the 143 CTA subway and elevated rail stations and 4,267 spaces at 50 of the 76 Metra suburban rail stations. Moreover, indoor or sheltered parking is available at 83 CTA stations, more than any other transit system in North America. The specific location of bike racks inside the stations provides both weather protection and greater

security, since they are usually placed within easy sight of station attendants and other passengers. Chicago is currently installing additional sheltered bike parking for 382 bikes at four CTA stations, and the city has funding to install bike shelters for 250 more bikes in 2010.

The largest bike station in the USA is located in Chicago's Millennium Park, immediately above the terminal station for two of Chicago's suburban rail lines. The bike station is easily accessible from downtown Chicago and the 18-mile Lakefront Trail. It provides secure, indoor parking for 300 bikes as well as convenient lockers, showers and towel service, bike rentals, bike repairs, and guided bicycling tours.

The CTA regularly monitors bike parking needs by conducting bi-annual bike rack inventories and measuring usage rates. It then works with Chicago DOT to install additional racks where needed.

As in most of the case study cities, all of Chicago's buses have bike racks – including CTA buses as well as PACE suburban buses. Bikes are permitted on CTA and Metra trains except during weekday rush hours. And just as most of the other cities, no fees or permits are required for the use of bike racks on buses or for bringing bikes on trains.

The biggest challenge to bike-transit integration in Chicago is the difficult access to train platforms. Because most of the rail lines are so old, only 54% of CTA stations and 68% of Metra stations are ADA accessible. Thus, cyclists are often forced to carry their bikes up long flights of stairs. Few stations have elevators, and cyclists are not permitted to use escalators.

Chicago DOT, transit agencies, and the cycling community are aware of these problems and have made improvements in bike-transit integration a top priority. Chicago's Bike Plan 2015 sets goals of further expanding and improving bike parking inside and outside of rail stations, remodeling stations to make them more accessible to bikes, providing more park-and-ride facilities, and establishing a second bike station with better transit connections.

Toronto

The combination of high rates of transit use and rising cycling levels has prompted a range of efforts to integrate the two modes in the Toronto metropolitan area. The

main approach has been to provide ample bike parking. With over 15,000 post-and-ring bike racks throughout the city, Toronto has more bike parking than any other city in North America. That includes bike parking at almost all rail stations. In 2008, there were 1,192 short-term spaces in bike racks at Toronto Transit Commission (TTC) subway stations and 579 short-term spaces in racks at GO Transit suburban rail stations.

Yet there is a severe shortage of secure bike parking, with only 114 bike lockers in the entire transit network. Consequently, Toronto plans on greatly expanding the supply of secure parking in 2009 and 2010 through installation of more bike lockers and completion of a new bike station at Union Station, the main transit hub in downtown Toronto, providing bus, streetcar, subway, and suburban rail connections. The bike station will provide secure, sheltered parking for 200 bikes. Construction of an even larger bike station at City Hall is planned to begin in 2010. That facility will be close to several bus and streetcar lines. The GO Transit suburban rail system is improving its bike parking by expanding sheltered parking to all stations by the winter of 2009–2010.

As in most cities with high levels of rail transit use, bikes cannot be taken on TTC subways and streetcars during weekday peak hours. Even when permitted, there are no special provisions for bikes on TTC subway cars. Similarly, bikes are not allowed on any GO Transit trains headed toward Union Station in the morning peak (6:30–9:30) or departing Union Station in the evening peak (3:30–6:30). Folding bikes are permitted on all public transport vehicles at all times. Bike access to rail transit is limited by the lack of elevators in most subway stations. As in Chicago, cyclists in Toronto must carry their bikes up and down long flights of stairs to reach the train platforms. Only 41% of TTC subway stations are wheelchair accessible, while 75% of GO Transit stations are accessible, either through elevators or ramps.

Toronto is making rapid progress equipping its buses with bike racks, which can be used at any time, even during peak periods. In 2008 only 55% of TTC buses had bike racks, but all new buses have racks, and every month about 40 older buses are retrofitted with racks. By the end of 2010, all TTC and GO Transit buses will have bike racks, thus facilitating bike and ride throughout the region.

There is almost no explicit coordination of bike routes with transit routes and station stops. Instead, the guiding principle of bike route planning is to put every Torontonians within a 5-min bike ride of the bikeway network. The many transit stations and fine-grained street network in much of the central city facilitates bike access to TTC stations. In suburban areas, however, many streets are circuitous and do not connect across arterials, making it difficult for cyclists to avoid major arterials while en route to a transit station.

Although bike-transit integration in Toronto faces some serious challenges, much progress is being made, partly thanks to the Province of Ontario's Metrolinx BikeLinx Program, which helps finance bike parking at stations and bike racks on buses. With the two new bike stations, additional bike lockers, expansion of sheltered parking, and completion of bike rack installation on all buses by 2010, Toronto will have made great strides coordinating cycling and public transport.

Washington

Bike-transit integration in Washington is similar to the situation in the San Francisco Bay Area. Both metropolitan areas rely on regional metro systems started in the late 1960s and early 1970s: BART in San Francisco and Metrorail in Washington. There is bike parking at almost all of Washington's 86 Metrorail subway stations, with a total of 1,800 bike racks and 1,300 bike lockers. The parking facilities are popular, with usage rates at most stations ranging from 50% to 100%. In October 2009, a new bike station with spaces for 150 bikes will open next to Union Station, providing convenient connections to Metrorail as well as suburban trains leaving from Union Station. The bike station will also offer bike rentals, repairs, and accessories as well as storage lockers and changing rooms.

In 2008 a new bike sharing program began in Washington, similar in technology to the Velib system in Paris, but on a much smaller scale: only 120 bikes compared to over 20,000 bikes in Paris. It facilitates bike-and-ride because eight of the ten bike sharing docking stations are at Metrorail stops. The short-term rental bikes can be used to get to and from Metrorail stations, thus serving as feeders and distributors for transit.

Bikes are allowed on Metrorail trains except during morning and afternoon rush hours on weekdays: two bikes per car on weekdays, four bikes per car on weekends. Unlike the much older subway systems in New York and Chicago, all 86 Metrorail stations have elevators (271 in total) and are ADA accessible. That facilitates access to platforms for cyclists as well, who are, in fact, required to use the elevators and are not permitted on escalators. In contrast to the Metrorail, VRE and MARC suburban trains do not allow bikes on board at any time unless they are folding bikes. All 1,450 WMATA buses have bike racks, but some buses run by suburban agencies do not.

In theory, bike plans for the Washington area establish the goal of coordinating bike routes with transit routes, but in fact, nothing has really been accomplished in this area except by accident. Overall, however, bike-transit integration in the Washington area is successful. The biggest gap is the exclusion of bikes from the Metrorail system during peak hours. To some extent, this is unavoidable due to the overcrowding of metro cars, just as on the BART, Toronto, and Chicago subway systems. But it reinforces the need to expand bike parking at the many Metrorail stations where current capacity is insufficient.

New York/New Jersey

With 55% of all work trips by public transport, New York City has, by far, the highest transit mode share of any city in North America. Thus, one might expect substantial efforts to coordinate cycling with public transport. In fact, New York City's transit systems have done little to promote bike-transit integration, far less than any other city in this study. The Metropolitan Transportation Authority (MTA) does not provide bike parking of any kind at the city's 467 subway stations, so the only option for cyclists is to park on nearby sidewalks. The MTA's suburban railroads, the Long Island Railroad (LIRR) and Metro-North Railroad (MNR), offer bike parking at some of their stations – but MTA has no information on the total number of spaces (MTA, 2009).

Compounding the problem of insufficient bike parking along the many subway and suburban rail lines of the MTA, there is no secure bike parking at any public transport terminals in Manhattan. Train, bus, and ferry terminals do not even offer short-term

parking in bike racks. Thus, cyclists must seek out the occasional bike rack on sidewalks within a few blocks of the terminals or risk having their bikes confiscated if parked at traffic signposts, which is illegal in New York.

NYC subways are unique in permitting bikes on board trains at all times, but it is difficult to get bikes to the platforms. Only 16% of New York's subway stations are ADA accessible via elevators or ramps. At the remaining 84% of stations, cyclists must carry their bikes up and down long flights of stairs, as they are prohibited from using escalators in stations where they are available. Bikes are allowed on the MTA's two suburban railroads (MNR and LIRR) except during peak hours in the peak direction, but cyclists must register in advance and purchase \$5 lifetime permits. Folding bikes are allowed at all times. In 2008, 18% of LIRR stations and 52% of MNR stations were not ADA accessible – considerably less than the 84% inaccessible MTA subway stations, but still a problem for cyclists having to carry their bikes up and down stairs.

Bike-bus integration is almost non-existent in New York City. Not a single bus in the MTA's fleet of 5,929 buses has a bike rack. That contrasts sharply with 100% of buses equipped with bike racks in most of the other case-study cities. Only since spring 2008 have folding bikes been allowed on most MTA buses.

There is no explicit effort to coordinate bike routes with transit routes in New York City. That is not a severe problem in most of the city because the transit network is so dense that most neighborhoods are served by a nearby subway or bus line. In the suburbs and the outermost portions of the city, however, the complete lack of bike-transit route integration is a serious shortcoming. Precisely in those lower density areas where cycling would provide an ideal feeder mode to more distant transit stops, bikeways are almost exclusively recreational paths that do not connect to practical destinations such as transit stations.

Not only does New York compare unfavorably in its bike-transit integration to the seven other case study cities, but it is surpassed by the New Jersey portion of the Greater New York metropolitan area. In 2008, New Jersey Transit (NJT) offered bike parking at 90% of its suburban rail stations and 80% of its light rail stations, with a total of 2,400 spaces, including 376 secure bike

lockers. Unlike the MTA in New York, NJT provides bike racks at all three of its major terminals in Hoboken and Newark (Penn Station and Broad Street). Bikes are allowed on all suburban rail and light rail lines except during rush hours in the peak direction, and no permits or fees are required. Folding bikes are allowed on all NJT vehicles at all times. Roughly half of NJT's 2,000 buses are equipped with bike racks, and an additional 200 buses are outfitted with racks each year. By 2014, 95% of NJT's buses will have bike racks. The main problem in New Jersey is the almost complete lack of bike paths and lanes leading to NJT rail stations and bus stops.

Summary of Case Studies

Most of the case study cities have greatly improved the coordination of bicycling and public transport in recent years. They have increased bike parking at transit stops and better accommodated passengers wanting to take their bikes with them on buses and rail vehicles. Only a few transit systems have measured the actual extent of bike and ride, but the available evidence is encouraging. In Washington DC, for example, the number of bicyclists riding on Metrorail increased by 60% between 2002 and 2007. At some stations, cyclists accounted for up to 4% of all passenger boardings. In Minneapolis, Metro Transit carries over 250,000 bicycles annually and reports a doubling of bikes on buses between spring 2007 and fall 2008. Roughly 4% of Portland MAX light rail passengers carry their bikes onto the vehicles with them. In the San Francisco Bay Area, the share of passengers accessing BART stations by bike rose from 2.5% in 1998 to 3.5% in 2008, with an average of 10,920 bike-and-ride trips per day.

As shown in [Table 1](#), there is considerable variation among the eight case studies. The San Francisco Bay Area, for example, provides the full gamut of bike-integration measures and has been at the vanguard of innovations to promote bike-and-ride. By comparison, New York's transit systems have made few provisions to accommodate cyclists, lagging behind the other case study cities in both the quantity and quality of bike-integration measures. All eight of the cities have plans to further improve bike-transit integration. Thus, it seems certain that the promising trends of recent years will continue.

Bicycle Integration with Public Transport. Table 1 Overview of bike-transit integration measures in eight large American and Canadian cities [37–54]

Bike parking at transit stops and stations	Bikes on transit		Bike routes and transit stops	Highlights: strengths and challenges
	Bike racks on buses	Bikes on trains		
San Francisco (population city: 0.8 m, metro: 4.2 m)				
BART provides 4,313 bike parking spaces, including 716 conventional and 294 electronic bike lockers	All buses have bike racks (usage rates vary from 17% to 43%)	BART allows bikes on all non-peak trains and during peak times in non-peak directions. BART expanded on-board space for bikes on select cars	Bike routes often parallel MUNI bus routes and intersect with transit stops. No explicit planning process coordinating transit and cycling routes in SF	Strengths: Racks on all buses; extra space for bikes on Caltrain cars; bike access to BART off-peak; extensive bike parking at BART and Caltrain stations; five bike stations
Caltrain's 32 suburban rail stations offer 400 bike racks and 1,100 bike lockers		Caltrain: special lead cars designated for bike use all day, space for 16–32 bikes	The Regional Bicycle Plan as well as the Bike Plans of BART and Caltrain encourage coordination of bike routes and facilities with public transport	Challenges: No bike access on MUNI light rail; need more dedicated space for bikes on Caltrain; no coordination of bike routes with MUNI routes; no rush hour access for bikes on BART
Five bike stations with 659 bike parking spaces at BART and Caltrain Stations				
Portland (population city: 0.5 m, metro: 2.1 m)				
Bike racks and/or lockers at almost all TriMet LRT stops and transit hubs providing 670 bike parking spaces; including 320 secured spaces	All buses have bike racks	MAX light rail: bikes permitted if space is available on cars, but non-cyclists passengers have priority	Explicit coordination of bike routes with transit stops with the goal of establishing a seamless link between the two modes	Strengths: Racks on all buses; dedicated space on LRT for hanging bikes near doors; free access for bikes 24/7; easy access to low-floor trains
15 downtown locations with bike lockers; usually close to light rail or bus stops				Challenges: Lack of good quality and quantity of parking at most train stations; poor design of access to stations by bike; cyclists are often denied boarding on LRT during peak
Vancouver (population city: 0.6 m, metro: 2.1 m)				
660 bike parking spaces in bike racks at SkyTrain stations and at transit transfer nodes	All buses have bike racks	SkyTrain: bikes allowed anytime except in peak periods in peak direction	Central Valley Greenway and BC Parkway facilitate access to and from transit stations	Strengths: Bike racks on all buses; bikes allowed on SkyTrain except during peak hours in peak direction; integration of bike network and transit stops; bike parking at all major transit stops; 24/7 no cost bike access on SeaBus
400 secure bike lockers at most Sky Train and all West Coast Express stations		SeaBus: bikes allowed at all times	Translink's \$2.55 million annual cost sharing of cycling infrastructure favors projects that facilitate access to transit	Challenges: Need more and better bike parking; need more capacity on SkyTrain to accommodate cyclists

Bicycle Integration with Public Transport. Table 1 (Continued)

Bike parking at transit stops and stations	Bikes on transit		Bike routes and transit stops	Highlights: strengths and challenges
	Bike racks on buses	Bikes on trains		
Minneapolis (population city: 0.4 m, metro: 3.2 m)				
271 bike parking spaces and 226 bike lockers next to Metro Transit stops and at park-and-ride lots. Usage rate of 28% of bike parking spaces at Hiawatha LRT line	All buses have bike racks. Bike on bus demonstration racks in various locations	27 light rail vehicles with on-board interior vertical racks that accommodate 4 bikes per vehicle	No explicit coordination of bike routes and transit. But connection to transit lines is a prioritizing criterion for bike projects funded by the MPO	Strengths: Bike racks on buses and trains; bike racks and lockers at most train stations; marketing information on bike transit integration provided by Metro Transit
City bicycle ordinance encourages parking bikes at sign posts, which are within a block of most bus stops. Bike station 1/10 of a mile from the Chicago and Lake Street transit hub			The Hiawatha LRT line parallels an off-street bike path for most of its length in Minneapolis	Challenges: Bike racks needed at four more LRT stations; lack of bike paths and lanes leading to train stations and bus stops
Chicago (population city: 2.7 m, metro: 9.5 m)				
2,153 bike parking spaces at 131 of the 143 CTA stations and 4,267 bike parking spaces at 50 of the 76 METRA suburban rail stations. Most (83) CTA stations provide indoor or sheltered bike parking. Usage rates of 90% and 50% for indoor and outdoor racks	All CTA and PACE buses have bike racks	Bikes permitted on CTA and METRA trains during off-peak. Bikes not permitted on escalators in stations	The routing of on-street bikeways in Chicago takes the location of transit stations into account. CTA system maps show bike parking possibilities at stations	Strengths: Ample bike parking at 131 CTA stations, of which 83 provide indoor parking. State-of-the-art Millennium bike station at downtown terminus of suburban rail line; CTA regularly collects bike rack usage data to add parking where needed
Largest bike station in the USA with indoor parking for 300 bikes, right above the terminal station for two of Chicago's suburban rail lines				Challenges: The CTA subway is old with limited ADA facilities; flights of stairs make it difficult to bring bikes on board
Toronto (population city: 2.5 m, metro: 5.5 m)				
1,771 short-term bike parking spaces and 114 bike lockers at TCC subway and GO Transit stations	55% of TTC buses and all GO Transit buses have bike racks	Bikes permitted on TTC subways, RT trains, streetcars, and buses without bike racks except during peak hours	The guiding principle of bike facility planning is to put every resident within a 5 min bike ride of the bike network	Strengths: Extensive transit system with high mode share; bike racks on most buses; bikes allowed off-peak on streetcars, subways, and suburban rail; bike parking at most transit stops

Bicycle Integration with Public Transport. Table 1 (Continued)

Bike parking at transit stops and stations	Bikes on transit		Bike routes and transit stops	Highlights: strengths and challenges
	Bike racks on buses	Bikes on trains		
New bike station at Union Station (opening spring 2009) with secure, sheltered parking for 200 bikes. Second bike station planned	All TTC buses will be equipped with bike racks by end of 2010	Bikes permitted on GO Transit trains except on trains arriving and departing from Union Station in peak direction	The Waterfront Trail which spans the Greater Toronto Area parallels the busy GO Rail Lakeshore corridor and is in close proximity to many stations	Challenges: No bikes allowed on rail transit during peak hours; lack of elevators in many stations; more bike parking and secure lockers needed at stations; no coordination of bike routes with transit stops
Washington, DC (population city: 0.6 m, metro: 5.3 m)				
1,800 bike racks and 1,300 bike lockers at Metro stations. No bike parking at bus stops, except major transit hubs with rail stations	All WMATA buses have bike racks	Bikes allowed on Metro trains during off-peak. Cyclists must use elevators between the street and the station platforms	Drafting of DC bike plan took the location of metro stops into account, particularly for the bike route network and facility recommendations	Strengths: Bike racks on all buses; bikes on Metro except during peak; lockers and racks at all stations; SmartBike short-term rentals at 8 Metro stations
Bike station for 150 bikes to open in July 2009 at Union Station		Bikes not allowed on MARC trains. VRE allows bicycles on some trains		Challenges: Restricted bike access hours on Metro; bikes restricted on VRE and MARC suburban rail
New York City (population city: 8.2 m, metro: 18.8 m)				
No dedicated bike parking at rail stations or transit terminals. Some bike parking provided by NYCDOT on sidewalks, often near transit stops. No secure bike parking of any kind in NYC	No buses with bike racks in NYC; Roughly half of NJ Transit busses have bike racks in 2010 (planned increase to 95% by 2014)	Bikes permitted on the NYC subway at all times, but only 16% of stations ADA accessible, with elevators or ramps	No explicit coordination; but the transit network in the city is so dense that most of the bike network is close to transit	Strengths: 24/7 bike access and no fees or permits on NYC subway system, most extensive in North America; big increase in bike racks and bike parking on NJ Transit
Bike parking at a third of MTA suburban train stations in NYC; bike lockers at 18 LIRR and 6 MNR stations; bike parking at 90% of NJ Transit train stations and 80% of LRT stations (a total of 2,400 bike parking spaces, with 376 bike lockers)		All suburban trains allow bikes on board during off-peak hours, but limit of 2–4 bikes per car on weekdays; NJ Transit LRT allows bikes on trains during off-peak hours with a maximum of 4–6 bikes	No coordination of bike network with transit stations and routes in suburbs; most suburban cycling facilities are recreational and do not lead to transit stops	Challenges: No bike racks on MTA buses in NYC; limited parking at MTA suburban rail stations and no bike parking at two main train stations in Manhattan; no secure bike parking; difficult to access platforms: only 16% of subway stations with elevator access

Future Directions

North American cities have been making impressive progress integrating cycling with public transport. Since 2000, the percentage of buses with bike racks has almost tripled. Bike-rail integration has also advanced. Most light rail, metro, and suburban rail systems permit bikes on their rail vehicles except during peak hours, and they increasingly provide special accommodations for cyclists such as bike hooks, racks, and rails in special areas of rail cars. Complementing provisions for bikes on transit vehicles, bike parking at transit stops has been vastly expanded over the past 10 years, with large increases in the number of racks as well as improvements in the convenience, security, and shelter of bike parking.

While cycling and public transport have considerable synergies, there are some inevitable conflicts. Surveys in some cities indicated that cyclists prefer to take their bikes with them on rail vehicles so they can use them at both ends of the trip. That can cause problems during peak hours, however, when all available capacity is needed to accommodate passengers, and there is no extra room for bikes. Taking bikes on buses is much less of a problem since bike racks are external and do not reduce passenger-carrying capacity. But even bike racks can be filled to capacity during the peak, forcing cyclists to wait for later buses.

Paradoxically, bike-and-ride can become problematic where it is most successful. Capacity problems are most likely to arise in cities with well-used public transport and high levels of cycling. That is why the European approach to bike-and-ride has favored the provision of ample, sheltered, secure bike parking at transit stops instead of accommodating bikes on transit vehicles. Similarly, in North American cities with overcrowding of rail vehicles during rush hours, the focus should probably be on providing improved bike parking at rail stations. Not only is more parking needed, but it should be of higher quality, with more sheltered and secure spaces. Major transit terminals should include multi-service bike stations, such as those in northern Europe. Similar to the concept of “complete streets,” an appropriate goal of transit

systems in North America should be to provide “complete stations,” which fully accommodate the needs of cyclists. That includes making rail platforms more accessible to cyclists, which would also improve accessibility for persons with disabilities.

Such bike-and-ride provisions cost money, but they are much cheaper than park-and-ride facilities for motorists [15]. Transit systems should shift their focus from park-and-ride to bike-and-ride, which is more cost-effective as well as more environmentally friendly. To encourage that shift, federal, state, and local government agencies should vastly expand funding for further improvements in bike-and-ride measures.

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Bioaccumulation/Biomagnifications in Food Chains

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Article Outline

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Glossary

Bioaccumulation An increase in the concentration of a substance obtained from the abiotic environment in one or more tissues of an organism. Bioaccumulation occurs within a given trophic level.

Bioconcentration An increase in the concentration of a substance from the abiotic and biotic environment in one or more tissues of an organism. Bioconcentration occurs within a given trophic level.

Biomagnification An increase in the concentration of a substance obtained from organisms at lower trophic levels by an organism at a higher trophic level.

Biosynthesis Many molecules that can be bioaccumulated or biomagnified by organisms at higher trophic levels enter the food web by being synthesized by organisms at lower trophic levels.

Food chain The simplest possible representation of producer–consumer relationships in an ecosystem.

Food web The representation of the network of producer–consumer–degrader relationships in an ecosystem.

Depuration The metabolic alteration and excretion of a substance, usually a xenobiotic molecule.

Trophic level The position in a food chain or food web occupied by a producer or consumer of food.

Definition of the Subject

In a meta-analytical review of biomagnification in marine ecosystems, Gray [1] noted that more than half of the papers purporting to study this topic were using the term incorrectly [1, p. 46]. He then went on to propose careful definitions of the ways in which xenobiotics can gain entry into organisms. As noted above in the glossary, bioaccumulation, bioconcentration, biomagnification, and biosynthesis of substances represent four different routes of entry. Bioaccumulation, bioconcentration, and biosynthesis typically account for the presence of toxic molecules in organisms at low trophic levels, with transfer of compounds from environment to organism via cell membranes in small organisms with high surface-to-volume ratios, and via gill membranes in many larger aquatic species. Accumulation of xenobiotics via biomagnification is more likely to be a phenomenon that occurs in larger animals at higher trophic levels. The suite of processes that leads to the accumulation of toxic compounds in organisms has been an important element of ecological research for decades and an issue of great practical concern relative to anthropogenic impacts on biological communities [2] as well as to the health and well-being of human populations [3].

Introduction

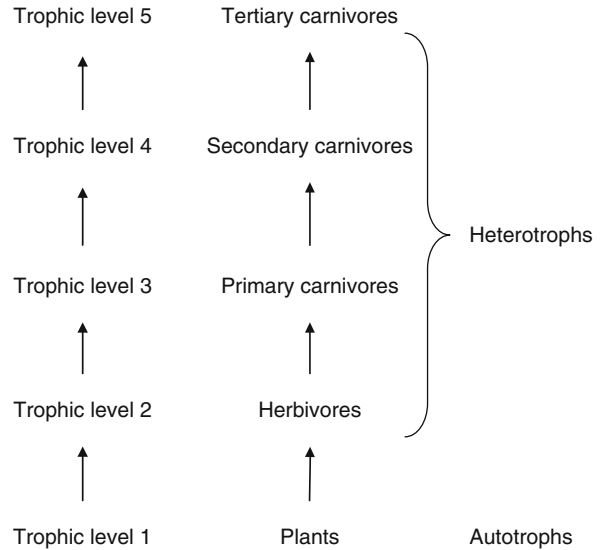
The Fundamental Ecological Context and Simple Food Chain Theory

A brief review of food chain theory will aid in understanding the processes that can lead to magnification of a non- or poorly metabolizable natural toxin or a non-biodegradable pollutant in a food chain. It is within this context of basic ecological principles that we can best view the movement, concentration, and/or transformation of such compounds that result in the degree of magnification that we find expressed in nature.

All animals need food to survive. Food may be burned (i.e., respired) to provide energy, incorporated into the animal's biomass as proteins, fats, and/or carbohydrates to provide essential structural or metabolic needs, or directed toward reproduction. Food used for these purposes takes the form of organic compounds that are collectively composed of (primarily) carbon, hydrogen, oxygen, nitrogen, phosphorus, and (secondarily) literally dozens of other elements. Organic compounds are produced from inorganic molecules such as carbon dioxide and water by a special category of organisms called autotrophs, or primary producers. Plants are the autotrophs with which most persons are familiar. They use the energy in sunlight to effect the transformation of inorganic compounds into organic matter and hence are called photoautotrophs. Less familiar to many people are the autotrophic bacteria that use chemical energy released from the mediation of oxidation–reduction reactions to synthesize organic matter from inorganic compounds. Such bacteria are referred to as chemoautotrophs. All living organisms that lack the ability to convert inorganic compounds into organic matter are called heterotrophs and depend either directly or indirectly on primary producers as a source of food.

The production of biomass by heterotrophs involves the conversion of one form of organic matter into another, a process called secondary production. Heterotrophs that eat plants are called herbivores. Heterotrophs that eat other heterotrophs are carnivores. Heterotrophs that eat herbivores are primary carnivores, and heterotrophs that eat primary carnivores are secondary carnivores. Not all heterotrophs are so easily classified. For example, some animals have rather cosmopolitan feeding habits and are called omnivores. Other heterotrophs feed primarily on nonliving organic matter (e.g., dead animals or the waste products of other heterotrophs) and are called detritivores. Regardless of whether the consumer is a herbivore, carnivore, omnivore, or detritivore, it is possible to make some broadly relevant generalizations about what happens to organic matter once it has been synthesized by autotrophs.

The successive transfers of food from prey to predator make up what is called a food chain. Each component of such a food chain is called a trophic level. Autotrophs are logically assigned to the first trophic



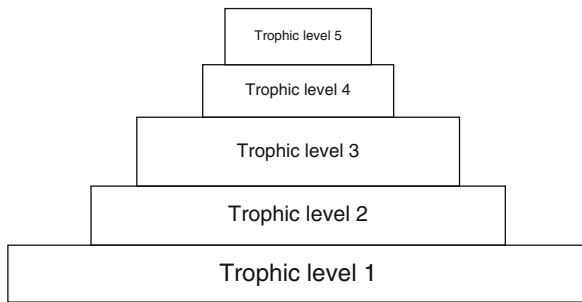
Bioaccumulation/Biomagnifications in Food Chains.

Figure 1

Diagram of a simple grazing food chain with plants as the first trophic level. Arrows indicate transfers of biomass

level in such food chains, herbivores to the second trophic level, primary carnivores to the third trophic level, and so forth (Fig. 1).

In most natural systems only a small percentage of consumed food is passed along from one trophic level to the next highest trophic level. This percentage is referred to as an ecological efficiency and is typically no more than 20%. This means that the rate at which food is ingested by a trophic level is at least five times greater than the rate at which food is passed on to the next trophic level. Most of the consumed food is either respired or excreted. Because ecological efficiencies are low, the flux of food from one trophic level to the next steadily decreases as one moves up a food chain, and the steady decrease in the flux of food to higher and higher trophic levels usually results in decreases in the biomass of organisms at successively higher trophic levels. A caveat to this last generalization is associated with the fact that organisms at successively higher trophic level tend to become progressively larger, i.e., predators tend to be larger than their prey. There are exceptions to this generalization, mainly in the cases of predators that hunt in packs or groups, such as wolves or killer whales. Because large animals generally require less food per unit biomass to sustain themselves than



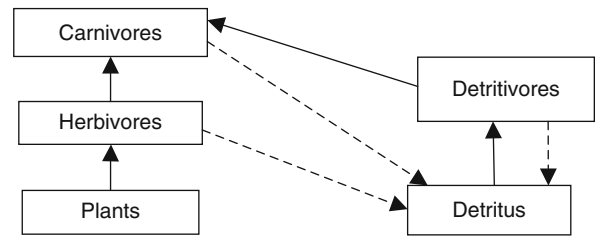
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Figure 2

An ecological pyramid. The decrease of biomass on successively higher trophic levels reflects the combined effects of low ecological efficiency and decreasing food requirements per unit biomass on higher trophic levels. Length of horizontal bars is proportional to biomass

small animals, the amount of biomass on successively higher trophic levels does not usually decline as much as one might expect based on the magnitude of ecological efficiencies, but in general one finds a decrease in total biomass at successively higher trophic levels. In other words, although the animals tend to be larger, there are a lot fewer of them. If the total biomass on successive trophic levels is represented by a series of horizontal bars, and if those bars are stacked on top of one another, the resultant figure has the appearance of a pyramid. That pyramid is called an ecological pyramid (Fig. 2).

The food chain consisting of plants, herbivores, and carnivores is often called the grazing food chain. Complementing the grazing food chain is another whose first trophic level consists of nonliving organic matter, i.e., dead remains of animals and plants and organic waste products excreted by heterotrophs. This nonliving organic matter is called detritus, and the associated food chain is called the detritus food chain. Simplistically, it consists of detritus, detritivores, and carnivores, and at the last step, the detritus food chain merges with the grazing food chain (Fig. 3). In a healthy ecosystem these two food chains work together to consume almost all the organic matter produced by the autotrophs. It is very important that the organic wastes produced by heterotrophs are consumed by detritivores, because such waste products are almost invariably toxic to the organisms that produce them. One food chain's waste is the other food chain's food,



Bioaccumulation/Biomagnifications in Food Chains.

Figure 3

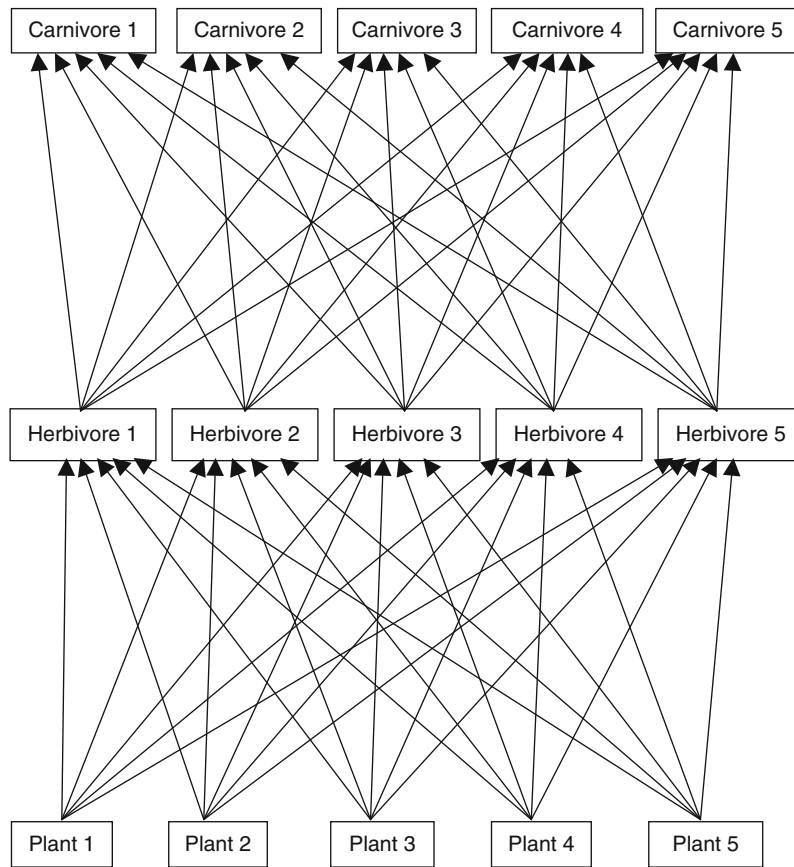
Interactions between the grazing food chain (*left*) and detritus food chain (*right*). *Solid arrows* indicate grazing, i.e., consumption of prey (food) by a predator. *Dashed arrows* indicate excretion and/or death

and of course, the carbon dioxide produced by the respiration of all heterotrophs is needed by all autotrophs for primary production. Thus the production and consumption of organic matter in a healthy community of autotrophs and heterotrophs is characterized by a great deal of recycling.

A variation on the concept of food chains is the depiction of feeding relationships as food webs (Fig. 4), in which the feeding relationships of (typically) individual species are represented in a two-dimensional diagram. Since a given predator may feed on more than one and perhaps many different prey species, such a diagram tends to have a very complex appearance and has the general characteristics of a web as opposed to a chain. However, careful examination of the feeding relationships depicted by a food web often reveals a pattern consistent with the food chain model. And the principles that govern the fate of consumed food apply regardless of whether feeding relationships are depicted by a food web or food chain. For purposes of this chapter, we will rely on the food chain model to rationalize/explain issues that arise from biomagnification, and we will use the interactions between the grazing and detritus food chains to illustrate how recycling can lead to results that are somewhat counterintuitive from the standpoint of simple food chain theory.

Food Chain Magnification Principles

Given the rather low ecological efficiencies that characterize most food chains, it is not hard to imagine how



Bioaccumulation/Biomagnifications in Food Chains. Figure 4

Feeding relationships in a hypothetical food chain in which each of five plant species is grazed by each of five herbivore species, which in turn is grazed by each of five carnivore species. The arrows depicting the feeding relationships have the appearance of a web, and such diagrams are characterized as food webs. In this particular case, however, the flow of organic matter could be just as well represented by a simple food chain consisting of plants, herbivores, and carnivores, as on the left side of [Fig. 3](#)

the concentration of a relatively refractory substance might be magnified from one trophic level to the next. Assume for the sake of argument that xenobiotic substance X cannot be respired. This would be the case, for example, if X happened to be a metal such as lead or cadmium. Assume further that for whatever reason X is not effectively excreted. This happens to be the case for methylmercury. For humans, about 95% of ingested methylmercury is, at least initially, retained by the body. Assume as a worst case scenario that X is neither respired nor excreted and instead is retained with 100% efficiency in the body of the consumer organism. If the ecological efficiency in the food chain is 20%, then the concentration of X in the food consumed by one

trophic level will be magnified by a factor of five in the food consumed by the next trophic level. In a grazing food chain consisting of five trophic levels, beginning with plants and ending with tertiary carnivores, the concentration of X in the tertiary carnivores should be $5^4 = 625$ times higher than the concentration of X in the plants. The fact that the concentrations of ostensibly refractory xenobiotics are sometimes found to be very high in the tissues of top-level carnivores has naturally led to speculation that exactly this sort of mechanism, i.e., biomagnification or food chain magnification, is responsible.

To illustrate this point, [Table 1](#) shows concentrations of residues of the pesticide DDT in the water and

Bioaccumulation/Biomagnifications in Food Chains.**Table 1** DDT residues (DDT + DDD + DDE) in water and organisms taken from a Long Island Salt Marsh [2]

Organism	DDT residues (ppm)
Water	0.00005
Plankton	0.04
Silverside minnow	0.23
Sheephead minnow	0.94
Pickarel (predatory fish)	1.33
Needlefish (predatory fish)	2.07
Heron (feeds on small animals)	3.57
Tern (feeds on small animals)	3.91
Herring gull (scavenger)	6.00
Fish hawk (osprey) egg	13.8
Merganser (fish-eating duck)	22.8
Cormorant (feeds on larger fish)	26.4

in various organisms taken from a Long Island, New York, salt marsh [2]. The data illustrate how very low concentrations of toxic substances in the water and/or in organisms at low trophic levels may increase dramatically through the food chain. The residue concentrations increase steadily from the plankton to small fish, to larger and larger fish, and finally to fish-eating birds. The total concentration factor from plankton to fish-eating birds is about 600, which suggests that the concentration factor between successive trophic levels may be about a factor of 5 (see above).

Agreement between theory and observation does not, however, prove that the theory is correct. There are other processes that can affect the concentrations of xenobiotics in the tissues of animals. Fish, for example, must constantly pump water over their gills to breathe. It is certainly possible that direct transfers of xenobiotics from water to fish may occur through the gills. This exchange may lead to high concentrations in the tissues of the fish by a mechanism (bioaccumulation) that has nothing to do with food chains. In a classic study, Hamelink [4] demonstrated that the concentrations of DDT residues in the tissues of fish in experimental ecosystems were unaffected by whether the

DDT residues entered the fish directly from the water or through a combination of entry via the water and food chain. The implication was that the food chain route was, at least in that case, insignificant compared to direct uptake from the water. And in contrast to the Woodwell et al. [2] results, Harvey et al. [5] found no evidence for biomagnifications of DDT residues in Atlantic Ocean food chains. In fact, the DDT residues were highest in the plankton and were ten times lower in flying fish, which feed largely on plankton. During the 1960s, when DDT was being used extensively in the United States and many other countries, sharks were found to contain high concentrations of DDT residues, but barracuda, which are also top-level carnivores, contained about 100 times lower concentrations than sharks [6]. The implication of these and other studies is that high concentrations of xenobiotics in top-level carnivores is not *prima facie* evidence of biomagnification, and among organisms occupying ostensibly similar positions in a food chain xenobiotic concentrations may vary widely as a result of differences in the extent to which organisms bioconcentrate xenobiotics directly from the environment.

An additional concern is the interaction between the grazing and detritus food chains, which is overlooked in the simple paradigm of food chain magnification. The consequences of this interaction are illustrated by a study of Isaacs [7, 8] that concerned concentrations of cesium (Cs) and potassium (K) in the muscle tissues of fish from the Salton Sea and Gulf of California. Briefly, the Cs/K ratio had been found to increase by a factor of three between successive trophic levels in the grazing food chain of the Salton Sea. However, the Cs/K ratios in similar fish from the Gulf of California were independent of the trophic level of the fish and about 16 times higher than the Cs/K ratios in the algae. Isaacs [7, 8] developed a mathematically complex unstructured food web to account for these differences. Laws [9] showed that the same results could be explained by taking into account the recycling that occurs between the grazing and detritus food chains (Fig. 3).

The conclusion is that a great many factors can influence the concentrations of xenobiotics in the tissues of plants and animals. Biomagnification, or food chain magnification, is one of those factors. But interactions between the grazing and detritus food chain can

lead to results that are not predicted when the detritus food chain is ignored, and bioaccumulation in at least some cases can be more important than biomagnification in determining xenobiotic concentrations within organisms. With this introduction, we consider in detail two human health issues potentially impacted by biomagnifications, ciguatera fish poisoning, and methylmercury intoxication.

Ciguatera Fish Poisoning

History

At the 14th Conference of the International Society for the Study of Harmful Algae, Fraga [10] described what is believed to have been the first reported case of ciguatera fish poisoning, an incident that occurred in 1525 in the Gulf of Guinea. An entry in an old manuscript described a case that happened in a Spanish fleet led by Andrés de Urdaneta. The fleet was en route to the Pacific through the Strait of Magellan. The journal entry translates as follows:

- On this island, a very beautiful fish called barracuda was caught by the flagship, and the Captain General invited some of the captains and officers of the King. All who ate the barracuda fell ill from diarrhea and were unconscious, so we thought they had died; however our Creator wanted everyone to be saved.

The fish responsible for this incident, a barracuda (top-level carnivore), is a fish not infrequently implicated in ciguatera fish poisoning. This case was subsequently reported by other early chroniclers, demonstrating how important the incident was.

Five years later, Peter Martyr, the early historian of the West Indies, wrote that when people eat certain fish, they “are attacked by divers strange maladies” [11]. Interestingly, Martyr ascribed this poisoning to movement of a toxin through what we would now call a food chain, from an origin in a plant, to fish, to humans.

In 1601, Pedro Fernández de Quirós, a Portuguese navigator in the service of Spain, reported that his entire crew was poisoned after eating “pargo,” fish that may well have been snapper or grouper, that they caught while anchored off the island of Espiritu Santo in what is now Vanuatu [12]. The most descriptive of the early accounts of ciguatera, however, comes from the famous British explorer Captain James Cook. In his

journal entry for Sunday the 24th of July, 1774 [13], Cook wrote:

- “The Night before we came out of Port two Red fish about the size of large Bream and not unlike them were caught with hook and line of which most of the officers and some of the petty officers dined the next day. In the evening everyone who had eat of these fish were seiz’d with violant pains in the head and Limbs, so as to be unable to stand, together with a kind of Scorching heat all over the Skin, there remained no doubt but that it was occasioned by the fish being of a Poisoness nature and communicated its bad effects to everyone who had the ill luck to eat of it even to the Dogs and Hogs, one of the latter died in about Sixteen hours after and a young dog soon after shared the same fate. These must be the same sort of fish as Quiros mentions under the name of *Pargos*, which Poisoned the Crews of his Ships, so that it was some time before they recovered. We had reason to be thankfull in not having caught more of them for if we had, we should have been in the Same Situation.”

Another of Cook’s officers identified the suspect fish as “Groopers”; it is likely that the fish Cook’s men ate on the 23rd of July, 1774 were either snapper or grouper.

Nature and Extent of the Problem

Ciguatera fish poisoning (CFP) is a worldwide health problem that represents an example of biomagnification of a naturally produced marine toxin. CFP is a non-bacterial, food-borne disease associated with the consumption of seafood that originates from coral reef environments in tropical and subtropical regions of the world. Humans contract the disease by consuming reef fish that have accumulated ciguatoxins as a result of feeding in coral reef habitats. Public health institutions throughout the world rank CFP as the most common food-borne disease related to the consumption of marine finfish [14].

In the introduction to this entry, the distribution of concentrations of DDT residues in organisms representing various trophic levels in a Long Island salt marsh were shown to be positively correlated with trophic level. The biological world frequently does not present itself as being so orderly. The relationships

between concentrations of naturally occurring marine toxins and trophic levels are considerably more difficult to discern given the variability caused by the complexity of marine food web interactions [7–9]. The next few paragraphs will explore the scope of the CFP problem, including the organisms responsible for toxin synthesis, natural pathways of the toxin through food webs, and biological and clinical evidence related to ciguatera fish poisoning.

CFP represents an example of biomagnification of a marine toxin that is produced by natural processes and, while presenting substantial difficulties for quantification and study, affects humans like no other toxin from the marine realm. Early work by Randall [14], Banner et al. [15, 16], and Banner and Helfrich [17] indicated that ciguatoxin (CTX) was derived from food consumed by fish and showed that toxicity could be transferred to non-toxic fish via consumption of toxic fish. These contributions evolved into the food web concept for CFP that is the paradigm to this day.

CFP has affected coastal populations and travelers in tropical and subtropical regions throughout the world for centuries. From old ship logs noted above, through WWII chronicles when CFP was a serious problem for military troops stationed in Pacific island locales, to the present day, CFP has been a serious public health problem. Currently, there are at least 50,000 reported cases of CFP cases per year [18, 19], but due to the high degree of misdiagnosis and underreporting, it is estimated that the actual frequency of CFP cases is closer to 500,000 per year [20]. It is estimated that >50% of the populations of small islands in the Caribbean and South Pacific have suffered from CFP. Interested readers are directed to reviews by Lewis [21], Lange [22, 23], and Fleming et al. [24] for additional details on the degree of CFP incidence in populations inhabiting various locales.

Symptomology

CFP produces gastrointestinal, neurological, and cardiovascular symptoms. These normally develop within 12–24 h of eating contaminated fish. Gastrointestinal effects may disappear within 4 days. Normally gastrointestinal symptoms are followed by neurological symptoms. The gastrointestinal symptoms commonly

include diarrhea, abdominal pain, nausea, and vomiting. The neurological symptoms that ensue may include numbness and tingling in the appendages (e.g., hands and feet), dizziness, altered hot/cold perception, muscle aches, low heart rates, and low blood pressure. The key pathognomonic symptom is the neurological malady of reversal of hot/cold sensation, i.e., hot feels cold and cold feels hot. Such conditions are caused by the disruption of the “vernacular” that neurons use to communicate with one another, i.e., the ion signals involving sodium and potassium. The suite of symptoms associated with CFP is caused by ciguatoxin’s ability to increase Na^+ permeability through the Na^+ channels of excitable cells (e.g., neurons and muscle cells) that are open at normal resting membrane potentials. This enhanced excitability of the membrane in turn affects $\text{Na}^+ - \text{Ca}^{+2}$ exchange and mobilizes intracellular Ca^{+2} . The primary receptor site of the CTX action is the 5th domain of the Na^+ channel, where it causes increased sodium ion permeability and depolarization of the resting membrane. The prolonged depolarization of nerve cells is understood to cause the suite of sensory discomfort symptoms associated with CFP [25]. CFP symptoms may persist in some form for weeks, months, or even years [26]. Generally, the gastrointestinal symptoms and general weakness last about 1 week, but the neurosensory manifestations (e.g., muscle aches, tingling extremities, and thermal reversals) commonly represent the most prolonged discomfort. It is interesting that CFP intoxication does not confer any immunity in its victims; on the contrary, CFP intoxication results in a heightened sensitivity to ciguatoxin in the victim.

Fortunately, death from CFP is rare (i.e., <0.1%), and when it has occurred it was generally the result of respiratory failure due to cardiovascular shock induced by severe dehydration. Death is frequently associated with the consumption of internal organs of the fish (e.g., liver, brains, gonads, viscera, etc.) in addition to the muscle tissue that is usually consumed. Given the exceptional potency of ciguatoxin (CTX), the low death rate merits some discussion. The two most plausible explanations for the low frequency of fatalities associated with CFP are (a) the large size differential between the “average” human and the average serving of CTX-contaminated fish, and (b) the likelihood that ciguatoxin cannot biomagnify indefinitely in nature.

To understand the consumer meal size differential, consider a person weighing between 125 and 200 lbs who consumes an 8-oz portion of contaminated fish; that serving represents 0.25–0.4% of the biomass of the consumer. Since reef organisms do not attain a size of 125–200 lbs, the final “dilution” of the toxin at the point of the human is large with respect to the dilutions that are experienced at various junctures within the marine reef ecosystem. The second explanation is related to the effects that the CTX toxin has on the various animals within the marine reef ecosystem. The ingestion of the ciguatoxin via the consumption of a contaminated organism (lower on the trophic structure) has been shown to cause behavioral changes in animals [27]. If, as has been suggested, such impaired behaviors may make those infected animals more susceptible to death, it would present a natural truncation of the CTX magnification food chain. This, together with the roughly 300-fold dilution factor at the serving-human juncture, may be the reason that humans rarely ingest levels of CTX of sufficient magnitude to cause a fatality.

Environmental and Biological Controls

The distribution of ciguatoxic fish is frequently stated as being within the 35°N and 35°S latitudinal band. Patterns of CFP incidence are well known for the Pacific, Indian, and Atlantic oceans, as well as the Caribbean and Mediterranean Seas [28]. Nonetheless, recent scientific inquiries have suggested an even more expansive geographic scale for ciguatera incidence [29]. It has also been suggested that the latitudinal range for CFP is expanding as a consequence of warming sea surface temperatures associated with climate changes [30]. The relevance of the expanding latitudinal range lies in the fact that the inclusion of higher latitude regions will include some areas with high population densities, which suggests the potential for increased incidence rates. Several informative reviews on CFP may be found in Lehane and Lewis [31], Bienfang et al. [31], Dickey [26, 27], Dickey and Plakas [32], and references cited therein.

In contrast to the orderly increases of DDT residue concentrations in organisms at various trophic levels presented in the introduction to this entry, the biomagnification scenario for CTX is complex. The

difference for CTX is nested in the fact that the concentrations and potency of this naturally produced marine toxin are modified through the complexity of marine food web interactions. Reasons for the apparent complexity of CTX biomagnification include the following:

1. Precursors of the CTX toxin, gambiertoxins, are produced by a variety of dinoflagellates belonging to the genus *Gambierdiscus*. These species vary significantly in terms of their tendency to produce toxins and the potency of the toxin they produce.
2. Metabolites of gambiertoxins, the CTX toxins themselves, appear in a variety of chemical forms (i.e., congeners). Additionally, the toxins are potent at very low dosages and are odorless, tasteless, and highly resistant to destruction/detoxification.
3. Spatial and temporal environmental variability appear to influence the production and flux of CTX into fish populations.
4. The complexity of the marine food web leading to the distribution of CTX among fishes harvested by man presents multiple vectors that may lead to human maladies in a given situation.
5. Humans display variable sensitivities to and symptomologies from CTX intoxication.

A genus of single-celled algae called *Gambierdiscus* (division Phaeophyta, commonly known as dinoflagellates) produces the gambiertoxins that are the natural precursors of CTX. This genus of dinoflagellates does not form conspicuous blooms that color the water like some other dinoflagellates that are known to produce “red tide” aggregations. The *Gambierdiscus* species normally grow epiphytically on various macroalgae in coral reef ecosystems. The need of these sessile, benthic macroalgae for sufficient sunlight for photosynthesis accounts for the limitation of ciguatera to organisms that inhabit and derive most of their nutrition from the relatively shallow coral reef environments found in warm, tropical areas. *Gambierdiscus toxicus* was originally designated as a new genus and species by Adachi and Fukuyo [28]. Since then, at least ten new species have been added to this genus [33–36]. It has long been suspected that the various *Gambierdiscus* species differ significantly in their degrees of toxin production [33, 34, 37–41]. These dinoflagellates are consumed by herbivorous fish,

beginning the process of bioaccumulation and biomagnification through the reef food web. The herbivores are consumed by carnivores, which in turn are consumed by humans.

The Toxin

CTX is a polar, lipid-soluble, highly oxygenated polyether molecule; it consists of 13–14 rings that are fused by ether linkages into a ladder-like structure [42–48]. The seminal toxins that are produced by cells of *Gambierdiscus* are frequently designated as gambiertoxins. These are less polar than the ciguatoxins isolated from fish. These less polar precursors are considerably less potent than the CTX molecule found in high trophic level carnivores. Because the different *Gambierdiscus* species/strains often co-occur at various relative abundances and can vary with respect to their individual toxicities, the resulting variability of toxin flux into the food web has confounded monitoring efforts. Ciguatoxins are piscine metabolites of the gambiertoxins that are assimilated and metabolized through multiple trophic levels of the marine food web. Ciguatoxins in fish may comprise an assemblage of principal ciguatoxins and numerous closely related structural isomers and congeners. Toxins isolated from different regions and/or organisms have been shown to exist in a number of forms that have different molecular weights, chemical structures, and toxicities [42, 48–53]. The recognition of these congeners necessitated new nomenclature, and in the more recent literature an I, P, or C prefix refers to the ocean of origin (i.e., Indian, Pacific, or Caribbean), and a number following refers to a specific congener/form of CTX. Thus, P-CTX-1 would refer to CTX congener 1 isolated from the Pacific Ocean. There are currently understood to be 29 congeners of P-CTX, and 12 of C-CTX. More robust analytical methods have revealed important new details regarding the chemical structure of CTX and its congeners.

Ciguatoxin is one of the most potent natural toxins known; the intake of picogram (i.e., 10^{-12} g) amounts of toxin will cause clinical symptomologies in humans. Such potency at minuscule concentrations has presented imposing challenges to the analytical techniques that may be applied for measurement of CTX in

fish tissues. The need for sophisticated chemistry presents exceptional challenges for the quantitative analysis of CTX at concentrations that produce clinical symptomologies in humans. The equipment required for analyses of complex organic compounds such as CTX is expensive to purchase and maintain, and requires highly talented analytical chemists to operate. This requirement for CTX detection has been addressed by a variety of approaches over the decades. Early work involved a number of non-ciguatera-specific bioassay procedures using mouse neuroblastoma cells and various invertebrates and vertebrates; these were followed by radioimmunoassay, enzyme immunoassay, and immunobead assays [54]. More recent analytical developments have focused on chromatographic methods involving high performance liquid chromatography (HPLC) combined with mass spectrometry (MS) [27, 55–57]. These robust analytical techniques are very expensive and require sophisticated infrastructural support. An important consequence of this range in analytical procedures used for CTX analyses has been a lack of uniformity, sensitivity, and specificity of analyses used by investigators working in various regions over the years.

Variability of Incidence

Within areas that are known to be prone to CFP incidence, the distribution of toxic fish can be highly variable on small scales both temporally and spatially. This is thought to be due to ecological factors that influence the degree of dietary intake of CTX by fishes, the degree of CTX biotransformation that may occur, the age/growth rates of the fish, and rates of CTX excretion (which are normally slow, and on the order of months). As a consequence, ciguatoxicity has been found to vary seasonally, from species to species, and from location to location within fairly proximate areas. A species of fish in one area may be relatively free of ciguatera but found in close proximity to an area where that same species is highly ciguatoxic. Such heterogeneous distributions of ciguatoxic fish have been described for numerous locations throughout the Caribbean Sea, Indian, and Pacific Oceans, and have been attributed variously to the combined forces of the territorial nature of carnivorous reef fish, differences in the abundance and/or

toxicity of *Gambierdiscus* spp., or variations in feeding patterns between locations.

An example was described by Lewis [58] for the mid-Pacific location of Kiribati, where southern (Tarawa) and western (Maraki) reefs were known for high CFP incidence, but not other reefs in the vicinity. Dierking [59] showed similar spatial heterogeneity in the distribution of ciguatoxic *Cephalopholis argus* throughout coastal areas on the islands of Oahu and Hawaii, Hawaii. The biomass of *C. argus*, introduced to Hawaii from French Polynesia in the 1950s, now surpasses the biomass of all other reef predators combined, and is one of the principal species associated with CFP in this area. Dierking's [59] findings showed substantial (8% versus 24%) differences in the prevalence of toxic *C. argus* between the islands of Oahu and Hawaii, large variations in toxicity within sites, no clear patterns between sites on either island, and very weak correlations of toxicity and fish size. Similar lack of correlation of either incidence or severity of ciguatoxicity with fish size, and high degrees of spatial heterogeneity in the incidence of ciguatoxicity in *C. argus* has been shown by Bienfang and DeFelice (unpublished data; www.fish4science.com).

The complexity of the marine food web leading to ciguatoxic fishes that are consumed by man has challenged marine scientists who have studied the ecosystem looking for vectors that contribute to this human malady. There is evidence that individual *Gambierdiscus* strains differ considerably in their inherent ciguatoxin production capabilities [34, 39, 56, 60]. Laboratory studies have suggested that individual *Gambierdiscus* strains are adapted to particular environmental regimes (e.g., different relationships between light intensity and growth rate, toxicity and light intensity, temperature, and/or salinity [60–63]. Changes in the dietary intake of ciguatoxins within food webs leading to fish have been described as being influenced by a variety of stochastic changes in predator–prey relationships within areas. Despite a low correlation between changes in ciguatera incidence rates and catastrophic events, it has also been repeatedly speculated that anthropogenic disruptions (e.g., shipwrecks, dredging) and/or natural environmental disturbances (e.g., hurricanes, cyclones, coastal inundations) may lead to the availability of new

surfaces for colonization by macrophytic algae and/or the associated epiphytic *Gambierdiscus*.

The apparent differences in sensitivity of individuals to ciguatoxic fish and/or associated variability in the severity of symptomologies from CTX intoxication among afflicted victims, together with a high (e.g., 90%) degree of underreporting has also confounded elucidation of processes associated with ciguatera prevalence. Although symptomologies that are consistent with an interference with sodium channel activity are characteristically associated with CTX [27, 57], other biochemical aberrations have also been implicated [56, 64, 65]. Also, it is relatively infrequent that remains of a meal that apparently caused CFP in a human have been available for credible analysis of ciguatoxin. When possible, analyses have shown ciguatoxicity in humans at concentrations in fish ranging from 0.1 to greater than 1 part per billion P-CTX-1.

Evidence of Biomagnification

Despite all these vagaries in the databases associated with CFP, the role of biomagnifications is suggested by the fact that high-level carnivores are by far the fish most frequently associated with the presence of CTX. The data pertaining to CFP incidence in fishes comes from both clinical records and sampling studies that broadly examined various reef species for ciguatoxicity irrespective of associated incidence of reported symptomologies by humans. Not surprisingly, data from the clinical records have had considerably more influence on our perspective regarding the piscivorous vectors leading to CFP. This comes from the standpoints of both their numerical abundance and their role in initiating the broad-scale studies of ciguatoxicity across fish species inhabiting reef ecosystems in various geographic locations. CTX is capable of bioaccumulating through the food chain through herbivorous and carnivorous (i.e., predatory) reef fish.

The fish most commonly involved in CFP incidents within various geographic locations have been listed/prioritized in several summaries [54–56, 59, 66–71]. Such listings show that the fish species that are most commonly implicated with ciguatoxicosis are primarily carnivorous. The prominent carnivorous taxa include the barracudas (*Sphyraena* spp.), groupers (*Epinephelus*

spp.), jacks (*Caranx* spp.), snappers (*Lutjanus* spp.), mackerels (*Scomberomorus* spp., especially the Spanish mackerel), kingfish (*Seriola* spp.), and moray eels (e.g., *Gymnothorax* spp.).

Not all fish implicated in CFP are carnivores. Non-carnivorous taxa include the detritivorous/omnivorous surgeonfish (*Ctenochaetus* spp.), parrotfish (*Scarus* spp.), and wrasses (e.g., *Cheilinus* spp.). In the Pacific, the detritivorous grazer, *Ctenochaetus striatus* (a surgeonfish), is frequently ciguatoxic and is thought to be a key vector amplifying CTX up the food chain. High levels of CTX and other *Gambierdiscus*-associated toxins in biodetritus are believed to account for the frequency of ciguatoxicity in *C. striatus*, and occasionally, mullets (e.g., *Mugil* spp.) because both have detritivorous grazing behaviors [72]. The mouthparts of the *C. striatus* are especially well adapted for feeding on phytodetritus and certain filamentous macroalgae known to commonly be host to the epiphytic *Gambierdiscus* spp. Surgeonfish and parrotfish tend to be dominant families by weight on many coral reefs, and among the most common prey of larger piscivores. Interestingly, carnivorous species that are grown in tropical aquaculture settings have been shown not to display ciguatoxicity, despite the presence of *Gambierdiscus* spp. growing on the confining vessels used in the culture process [73]. This lack of ciguatoxicity due to bioaccumulation has been attributed to the fact that the majority of the nutrition of such cultured carnivores is provided through the provision of prepared feeds supplied to the culture systems, rather than (normal) grazing upon a heterogeneous suite of natural feedstuffs.

The perceived variety in CFP symptomologies between fishes from the Caribbean and Pacific has variously been attributed to differences in the gambiertoxins produced by different predominant *Gambierdiscus* species in these locales, and/or the portions of the fish traditionally consumed. Helfrich et al. [74] estimated that the relative toxicity of fish liver tissue was 50 times greater than that in the muscle tissue. Vernoux et al. [75] similarly showed that the relative toxicity of the liver and viscera tissues (e.g., brain, gonads, heart) was considerably higher than that of the muscle tissue. This has been attributed to the preferential sequestering of the lipid-soluble CTX

molecule in the most lipid-rich portions of the fish. Such differences in the portions of a given fish species that are actually ingested by an assortment of populations from various geographic and/or ethnic backgrounds confound the analysis of the degree of trophic-level influence independent from other, potentially aliasing factors.

The high trophic level barracuda (*Sphyræna* spp.) has been shown to accumulate and retain CTX in its muscle tissue for extended periods of time, and toxicity was shown to be inducible. Banner et al. [16] and Helfrich and Banner [76] fed *Lutjanus* sp. ciguatoxic fish and showed the induction of toxicity within 6 months, and the subsequent retention of potency for 30 months following the cessation of feeding ciguatoxic fish. There exist chemistry results suggesting that CTX precursors from dinoflagellates may be oxidatively biotransformed to numerous congeners within herbivorous and carnivorous fish [53]. Biomagnification effects also appear to be evidenced in the human symptomologies caused by the consumption of herbivorous versus carnivorous fish. Bagnis and Legrand [77] and Kodama and Hokama [78] reported that the ingestion of ciguateric herbivorous fish caused mostly gastrological and mild neurological symptoms, while the consumption of carnivorous fish was associated with a broader and more severe suite of symptoms. This was attributed to differences in the ciguatoxin congeners produced by various (predominant) *Gambierdiscus* species in these locales, inevitably leading to an assortment of compounds present in fish representing a range of trophic positions.

There are many obstacles to a clearer definition of the prevalence of ciguatoxic fish and/or the distribution of ciguatoxic fish within a species or trophic structure. These impediments include vagary due to the temporally sporadic and spatially patchy distribution of both the causative agent (*Gambierdiscus* spp.) and the feeding patterns of the herbivorous and carnivorous fish species that lead to human CFP intoxications. The primary evidence for the biomagnification of CTX up the trophic structure is found in both the higher frequencies of CTX incidence in carnivores and the severity of symptomologies that have been observed in association with human consumption of carnivorous fish versus herbivorous fish.

Methylmercury

Hg: Sources and Cycling

Mercury (Hg) is a heavy metal. In nature, it exists in three chemical forms. These include the pure, elemental form (i.e., the form that in times past was used in thermometers), inorganic mercury compounds (i.e., mercury salts), and organic mercury (mercury incorporated into organic molecules). If you are old enough to remember gasoline at less than a dollar per gallon, you probably remember mercury as that strange, heavy, silver liquid that you rolled around on the counter top or in your hand. You are also likely to associate it with thermometers. If you are younger than that, you are most likely to think of mercury as a pollutant.

Methylmercury in the form of compounds such as methyl mercuric chloride, CH_3HgCl , and dimethyl mercury, $(\text{CH}_3)_2\text{Hg}$, is the most common form of mercury in the food people eat and is primarily responsible for the adverse human health effects attributed to mercury. Methylmercury is highly toxic and is readily bioaccumulated and biomagnified in freshwater invertebrates, marine invertebrates, freshwater fish, marine fish, marine mammals, and terrestrial mammals (including humans). The majority of methylmercury in freshwater and marine aquatic systems is derived from the conversion of other forms of mercury; rarely is methylmercury directly discharged into aquatic systems [79].

Mercury distribution within the environment (i.e., atmospheric, terrestrial, and aquatic) is controlled by complex biogeochemical cycles and ecological interactions. Sources of environmental mercury input may be divided into natural and anthropogenic categories: The relative magnitude of these categories is roughly equal [80, 81].

Natural contributions include such sources as volcanic eruptions, forest fires, weathering of mercury-bearing rocks/geological deposits, and aquatic volatilization [82]. Volcanic eruptions are enormous contributors on a per-event basis, but rare in terms of event frequency. Forest fires are intermediate contributors on a per-event basis but represent a higher frequency of event than volcanic eruptions. The weathering of geological deposits represents a slow but continuous contributory process. Volatilization,

sometimes referred to as recycling, occurs when mercury is released back into the atmosphere as a gas from freshwater and marine aquatic systems. An example would be the breakdown of methyl mercury by sunlight [83].

The various natural inputs of mercury to the environment enter primarily to the atmosphere. Once in the atmosphere, mercury can circulate for years, during which time it becomes widely distributed throughout the planet [84]. Mercury deposition from the atmosphere to the land or water can occur in either aqueous or dry forms. Aqueous forms include rain, snow, sleet, hail, and fog. Dry forms include gas or particulates. The principal atmospheric contributor is rain. Atmospheric deposition may enter aquatic systems directly as rainfall, or indirectly as a result of either surface runoff from terrestrial systems (i.e., in streams and/or rivers) or percolation followed by subsequent input from groundwater [83].

The anthropogenic sources of mercury are those inputs that result from the activities of humans. These anthropogenic inputs can be divided into four categories: (1) area sources, (2) combustion processes, (3) manufacturing activities associated with metals, alkali, and cement, and (4) other industrial processes. Landfills, dental preparations (e.g., mercury fillings), and laboratory operations are examples of area sources. Examples of combustion processes include coal-burning power plants and/or the burning of any other fossil fuel, medical waste incineration, and municipal waste combustion. Other industrial processes include such things as discharges from mining operations, hydroelectric plants, and pulp and paper production.

The primary anthropogenic contributors of mercury to the environment include coal combustion, chlor-alkali production (i.e., production of chlorine and sodium hydroxide), waste incineration, and metal processing. The relative proportions of mercury emissions to the atmosphere, exclusive of the burning of biomass, are illustrated by data from the year 2000 [80]. Relative proportions of mercury emissions to the atmosphere were 65% from stationary combustion, 11% from gold production [85], 6.8% from non-ferrous metal production, 6.4% from cement production, 3.0% from waste disposal (municipal and hazardous waste, crematoria and sewage sludge

incineration), 1.4% from pig iron and steel production, 1.1% from mercury production (mainly for batteries), and 2.0% from other sources.

Methylmercury is the most toxic form of mercury. It is formed by the methylation of inorganic mercury [79]; methylation means a single carbon methyl group (i.e., CH_3^-) is transferred from an organic compound and becomes bound to an inorganic mercury ion (i.e., Hg^{2+}) [86]. Methylation can occur by either biotic or abiotic means, with the former being the principal mechanism [83]. Examples of such biotic methylation include catalysis by microorganisms that live in freshwater systems (lakes, rivers, wetlands, sediments, soils) and/or the open ocean [87]. To a lesser extent, mercury methylation sometimes can occur via natural processes such as photochemical reactions; these are termed “abiotic processes” [83]. Methylmercury rather than inorganic mercury is bioconcentrated because organisms at various levels in the food chain retain it more efficiently. Inorganic mercury enters bacteria via a specialized transport protein that takes the mercury across the lipid membrane of the bacterial cell wall; this uptake is a key first step in both the methylation and bioaccumulation of mercury [83]. In contrast to other forms of mercury, which are not reactive and thus diffuse out of the cell as fast as they enter, methylmercury is reactive. This is the key to its accumulation in bacterioplankton and phytoplankton, which initiates the bioaccumulation process throughout the feedweb.

Bacteria that contain methylmercury may be passed to higher trophic levels when they are consumed by bacterivores or particle feeders. Alternatively, the bacteria may excrete the methylmercury into the water, where it can become adsorbed to planktonic particles and/or nonliving particulate material suspended in ocean systems. Similarly, methylmercury can be adsorbed by marsh grasses or other microscopic or macroscopic aquatic plants in freshwater systems. Through this mechanism mercury can enter the foodweb when these plants are subsequently consumed by herbivores or detritivores.

Methylmercury may be biomagnified in both marine and freshwater aquatic food webs, i.e., the methylmercury concentrations (i.e., grams mercury per gram biomass) increase at successive trophic levels. Methylmercury concentrations have been shown to generally increase as mercury is passed from

invertebrates and/or herbivorous fish to piscivorous fish, and ultimately humans [88]. As was illustrated for DDT residues above, methylmercury concentrations in marine apex predators can reach a level orders of magnitude higher than the concentration present in the water. The extent of concentration at the highest trophic level is influenced by the number of trophic levels in the system [88]. Methylmercury has a half-life of approximately 2 years in aquatic organisms. Such a prolonged residence time results in its bioaccumulation within aquatic food chains [79]. By contrast, methylmercury has a half-life of about 50 days in human blood [89].

Mercury Poisoning: Human Symptomologies and Historical Examples

Mercury is a neurotoxin. Many adverse health effects are associated with its accumulation in the human body. These effects vary depending on the amount of mercury one is exposed to, time of exposure, the mode of entry to the human body, the chemical form of the mercury, and the age of the subject.

Methylmercury is easily absorbed through the gastrointestinal tract when ingested. Mercury readily binds to proteins and therefore is not easily eliminated. Unlike essential metals such as iron, copper, or zinc, the human body does not require mercury for any purpose. The toxicity of mercury is closely related to its tendency to bind to sulfur and selenium, and in particular to amino acids that contain these elements: cysteine and methionine in the case of sulfur, and selenocysteine, selenohomocysteine, and selenomethionine in the case of selenium. Methylmercury, for example, can form a complex with cysteine that resembles methionine. In this methionine-resembling complex, methylmercury may be transported freely throughout the body, including across the placenta and blood–brain barrier, as well as through breast milk.

The uptake of mercury by humans generally occurs via two modes. One is inhalation. Metallic mercury (Hg^0) may be present in ambient air, particularly downwind from coal-burning power plants. Alternatively, mercury may be released from dental amalgams, and as methylmercury (CH_3Hg^+) from the consumption of foods such as fish. The human body is better adapted for mitigating the potential toxic effects of

vaporous mercury, so health effects from this source are relatively rare and are generally limited to cases where the victim in question is in close and prolonged proximity to a source of elevated mercury in the atmosphere. Methylmercury, on the other hand, is the most biochemically active form of mercury. It affects the central nervous system and can cause irreversible damage to areas of the brain. Damage to the nervous system is the most prevalent of methylmercury effects on humans, but methylmercury exposure can also harm the lungs and kidneys [90] and has been linked to increased risk of cardiovascular disease [91–93]. The first symptom of methylmercury exposure in adults is generally paresthesia, a sensation of tingling on the skin. This usually manifests itself as numbness and tingling in the extremities, though paresthesia may also occur in other parts of the body as well. This is normally the first manifestation of damage to the central nervous system [94]. In cases where elevated, more extreme doses of methylmercury poisoning occur, the initial paresthesia symptoms may be followed by ataxia and generalized weakness. Ataxia refers to a wobbliness, unsteadiness, and general lack of coordination. It reflects dysfunctionality in the cerebellum and is manifested by the brain's failure to regulate body posture and/or direction of limb movements. Even higher doses may lead to dysarthria, i.e., the loss of vision, hearing, and finally severe tremors, coma, and/or death [95]. These severe symptoms have only been observed in people who repeatedly consumed fish that were contaminated directly by methylmercury from anthropogenic sources [94].

Because of the biochemical activity of methylmercury and thus its ability to cross the placenta, children exposed to methylmercury in utero display developmental impairments that reflect compromised brain function; these symptoms may include such things as lower IQ, decreased memory function, attention deficit, and/or impaired language skills. More serious physiological effects include motor difficulties, sensory problems, and mental retardation [96].

Physical and environmental parameters that influence methylmercury concentration in natural waters are water pH and dissolved organic carbon (DOC). Higher acidity and DOC increase methylation rates of mercury and enhance its mobility in the water, thus making it more likely to enter the food chain [97–99].

Additionally, algal blooms reduce the uptake of methylmercury in freshwater food webs [100].

Methylmercury released directly into aquatic systems can cause mass acute mercury poisoning in humans who consume contaminated fish and shellfish. Probably the most dramatic historical example of this occurred in Minimata, Japan. Minimata is considered to be one of the worst industrial disasters of all time. Between 1932 and 1968, a factory of the Chisso Corporation discharged roughly 27 tons of mercury into a waterway that fed directly into Minimata Bay. The factory was using mercury as a catalyst to produce acetaldehyde, a chemical employed in the manufacturing of plastics [101]. More than 3,000 people were “officially” recognized and reported by government officials as directly suffering from mercury intoxication. Later, however, estimates of the number of people from the contaminated area afflicted with health problems or left permanently disabled increased to two million [102]. The large difference between these two estimates of the number of Minamata Disease victims reflects the fact that a social stigma associated with the symptomologies caused denial and/or underreporting by the afflicted, the local populations, and the local/national governments.

The range and severity of the health effects from this incident of mercury poisoning were extreme. The afflictions included the various symptoms discussed above and extended to birth deformities and deaths. Public awareness of the incident became widespread at roughly the time of the birth of the environmental movement elsewhere in the world. The account of what happened was so highly publicized that mercury poisoning became known as “Minamata disease” [103, 104].

A similar event occurred in Niigata, Japan. Mercury waste from acetaldehyde production was released from the late 1950s to the early 1960s by the Shawa Denkō Corporation factory into the Agano River, 65 km upstream from Niigata. The quantity released remains unknown to this day [105]. The Minamata and Niigata examples illustrate instances where the use of inorganic mercury as a catalyst in an industrial process led to very serious impacts from methylmercury intoxication. Specifically, mercuric sulfate, HgSO_4 , was used to convert acetylene into acetaldehyde, a precursor for, inter alia, acetic acid and acetone; and mercuric chloride, HgCl_2 , was used to convert acetylene into vinyl

chloride, a precursor of polyvinyl chloride (PVC). Unfortunately in both cases a side reaction of the catalytic cycle led to the production of methylmercury, by far the most toxic form of mercury, and the methylmercury was discharged with the wastewater from the factories, with tragic consequence for segments of the local population. Such examples clarified and galvanized societies' awareness of mercury as a pollutant with potentially direct and dire human impacts. It is important also to understand that the Minamata and Niigata cases represent examples where large, direct inputs of mercury were being made to water basins of relatively small volume, and very close to large human populations. In these cases, the delivery:dilution ratio was heavily skewed toward the delivery side, and there was a high probability of frequent human interaction with the introduced mercury through both direct and indirect pathways.

A somewhat different example of mercury pollution occurred at Dryden, Ontario in Canada. In this case, the Dryden Chemical Company repeatedly discharged inorganic mercury into the Wabigoon River between 1962 and 1970. Total discharges have been estimated at ~ 9 tons. The mercury was discharged with the wastewater from a chlor-alkali plant, where once again inorganic mercury was being used, in this case to convert sodium chloride (NaCl) into chlorine and sodium hydroxide. The inorganic mercury subsequently became methylated in the natural environment (i.e., not within the plant itself), resulting in serious methylmercury pollution in the downstream freshwater system and its various aquatic components [106]. This case again involved substantial inputs of mercury directly into aquatic systems of relatively small volume and close to large human populations.

Fish and shellfish have not been the only contaminated food source associated with methylmercury poisoning in humans. Other foods such as grain [107, 108] and meat [109] have caused mercury-related health effects, the most notable of these examples being the Basra grain disaster. In the 1960s and 1970s, seed grain containing ~ 8 $\mu\text{g/g}$ mercury was shipped to Basra, Iraq. In Basra, it was coated with methylmercury as a preservative/fungicide. The seed grain was then distributed throughout Iraq with the expectation that it would be planted. However, people fed the grain to

livestock destined for human consumption. The mercury was biomagnified through the food chain from grain to livestock to humans. People also consumed the grain directly by using it to make flour for bread and related food products. The decision of people to consume the seed grain instead of planting it resulted in mass mercury poisoning. Ten thousand people died and 100,000 were severely and permanently brain damaged [107].

Humans are not the only victims of environmental methylmercury contamination. Due to a commonality of certain biochemical processes across all animal groups, methylmercury has the potential to adversely affect many wild and domesticated animals. Such effects have been most notable proximate to areas of contamination and have been most evidenced as diminished reproductive success in fish, fish-eating birds, and mammals [88, 110].

Etiology of Mercury Intoxication

As noted above, mercury has a strong tendency to bind to sulfur and especially to selenium, which are essential elements. Because of this tendency, mercury can compromise the functionality of essential sulfur-containing amino acids (cysteine and methionine) and selenium-containing amino acids (selenocysteine, selenohomocysteine, and selenomethionine). The term "essential" in this context refers to compounds that humans cannot synthesize. Such compounds must be obtained from the food people eat. The distinction between essential and non-essential amino acids is somewhat unclear, as some amino acids can be produced from others. Methionine, for example, can be converted into homocysteine, which in turn can be converted into cysteine. Thus, given an adequate supply of methionine from food, humans can produce all the cysteine they need. But humans cannot synthesize methionine and cysteine *de novo*, and for this reason the sulfur-containing amino acids are often considered to be a pool of nutritionally equivalent essential amino acids. Similar logic applies to the selenium-containing amino acids.

One of the important functions of these two groups of amino acids is their role in determining the so-called tertiary structure of proteins. Simplistically, proteins are polymers of amino acids, and the sequence of

amino acids determines the primary structure of the protein. Hydrogen bonds between sequences of amino acids (peptides) determine the localized secondary structures of protein molecules. The tertiary structure is the overall three-dimensional structure of the protein and requires that certain parts of the molecule be locked into place by various mechanisms that include disulfide bonds, which is why cysteine and methionine are so important. Selenoproteins are analogs of ordinary proteins but contain one or more selenocysteines in place of cysteine. They are common in animals, and in humans ~25 selenoproteins have been identified. Health effects associated with an inadequate supply of selenium in the diet are believed to reflect the body's inability to synthesize sufficient amounts of these selenoproteins.

Exposure Limits

The unfortunate, industrially related incidents discussed above focused the attention of both health officials and the public on the perils associated with mercury. These were cases where mercury was discharged directly into bodies of water from which the local populace removed and consumed seafood containing up to 40,000 $\mu\text{g Hg/kg}$. Such industrial events are extreme, and the resultant concentrations of mercury in fish and shellfish were far above background levels. But the fact is that mercury occurs naturally in the environment, and through perfectly natural processes it finds its way into food that people eat. Incidents such as Minamata and Niigata contributed to public awareness of health issues associated with mercury bioaccumulation and biomagnifications in food chains leading to humans and led to the question, how much is too much. Studies began showing developmental effects in children, in particular among island/coastal populations that primarily consume seafood [111–113]. Federal and global organizations (e.g., US Food and Drug Agency (FDA), US Environmental Protection Agency (EPA), United Nations Food and Agriculture Organization (FAO), and the World Health Organization (WHO)) also took notice and began instituting guidelines for the consumption of fish and shellfish. Advisories, though intended for the general population, carried particular focus on pregnant women, fetuses, and young children.

Currently the US EPA uses a Reference Dose of 0.1 $\mu\text{g methylmercury/kg body weight/day}$ as an exposure limit without recognizably adverse effects. This limit carries a safety factor of 10 from the lowest observed adverse exposure level and corresponds to a blood mercury level of 5.8 $\mu\text{g/L}$ or 5.8 parts per billion (ppb) mercury. Blood mercury levels below this value are considered to be without appreciable risk by the EPA [114]. The Joint FAO/WHO established a Provisional Tolerable Weekly Intake of Mercury (PTWI) of 1.6 μg of mercury/kg of body weight, somewhat higher than the EPA's recommendation. The WHO guideline of methylmercury intake is equivalent to a concentration in hair of 5 parts per million (ppm). Another study of mercury in hair conducted in the Seychelles Islands, where seafood consumption is significantly higher than average, found mercury levels in hair ranging from 7 to 26 ppm. The Seychelles study was supportive of the WHO guideline. Though the calculated FAO/WHO value for all adults was actually 3.3 $\mu\text{g Hg/kg}$ of body weight, the published value of 1.6 μg of mercury/kg of body weight, which was weighted in favor of the most susceptible segment of the population (i.e., pregnant women, fetuses, young children) came to be commonly cited and used. Currently, the level of concern for mercury in fish is set by the FDA at 1.0 mg Hg/kg fish tissue.

Mercury in the Oceanic Ecosystem

Mercury from both natural and anthropogenic sources finds its way into the ocean, is taken up by plankton, and then transferred to small planktivorous fish. This begins a process of food chain magnification as the mercury is transferred to larger and larger predatory fish, ultimately finding its way into top-level carnivores like the tuna, swordfish, and sharks that people eat. Such large predatory fish tend to have the highest mercury concentrations (i.e., $\mu\text{g Hg/kg}$ fish) and as such have attracted the most attention from the public, health officials, and scientists. The accumulation of methylmercury in high trophic level organisms results mainly from the ingestion of methylmercury-containing food (biomagnifications) rather than direct uptake of methylmercury from the water itself (bioaccumulation).

There are many factors that influence the concentrations of methylmercury in open ocean fish. These include size [115], age, trophic position [116, 117], physical and environmental parameters [100], and area of capture [118, 119]. There also remain large unexplained variations in the relationship of mercury concentration (i.e., $\mu\text{g Hg/kg}$ fish tissue) versus fish size. In general, one would expect that, within a given species, larger fish are older fish and have consumed more prey to attain their size. A relationship between fish size and mercury content of the flesh is evident for some marine carnivorous species such as *Seriola rivoliana* (common name, bonita or jack), *Acanthocybium solandri* (common name, wahoo, ono), *Lutjanus syagris* (common name snapper), and *Epinephelus guttatus* (red hind, grouper) [120].

The age of the fish and preferred depth of feeding appear to explain more of the variance in mercury concentration than does size [117, 118, 121, 122]. Depth of habitat and foraging were found to be highly correlated with mercury concentrations [123]. This is because dissolved organic mercury concentrations increase with depth [123]. In addition, deeper waters (i.e., below the thermocline) tend to have lower oxygen, which leads to enhanced methylation rates [124–127]. This has led to the recent conclusion that the source of methylmercury in the open ocean is the deep water column [128, 129] and not coastal runoff [130] or the euphotic zone [131]. Many large oceanic predatory fish regularly dive to great depths to forage for prey from waters having lower oxygen concentration.

Mercury and Selenium

The confusion generated by the guidelines from the various agencies, along with repeated media attention to the presence of mercury in seafood has led to significant misunderstandings concerning the safety of seafood consumption and the role of seafood in a healthy diet. This has been to the detriment of both the commercial fishing industry and the consumers who have been confused and/or discouraged from regularly eating seafood.

What are some of the reasons that the perceived risk from eating seafood is overestimated? First, there has never been a confirmed case of mercury poisoning from the consumption of tuna or any other open

ocean fish. The potential harmful effects of low levels of mercury from open ocean fish are undocumented and hypothetical. Mercury may be toxic at high levels, but not at the low levels typically found in oceanic fish. The joint advisory on seafood issued in 2004 by the FDA and EPA (www.cfsan.fda.gov/~dms/admeHg3.html) was for pregnant women, nursing mothers, and young children. It directed pregnant women, nursing mothers, and young children to avoid eating swordfish, sharks, king mackerel, and tilefish, to limit consumption of other forms of fish to two meals per week, and to limit consumption of tuna to one meal per week. There has never been an advisory directed at the general consumer to limit seafood consumption.

Scientists are now realizing that earlier studies and resulting consumer guidelines were flawed. In fact, deliberately avoiding fish may increase the risk of adverse nutritionally related health effects. The benefits of fish oils (i.e., the omega-3 polyunsaturated fatty acids) on brain development are known and widely accepted. The basis of this realization began when adverse child brain development effects were not seen in multiple follow-up studies in populations consuming ocean fish [132–134]. Omega-3 polyunsaturated fatty acids (PUFAs) are critical to normal development of the human brain and nervous system. Pregnant women and nursing mothers who avoid foodstuffs rich in omega-3 PUFAs without replacement from another source risk adverse effects on their child's brain development. The excessive caution associated with fish consumption reflected knowledge that the fetal brain is very sensitive to maternal exposure to methylmercury. It is true that methylmercury can impair selenoenzyme activities in the brain.

Further exploration, however, revealed that selenium, an essential trace element, is simultaneously present with mercury in most oceanic fish. The ratios of selenium to mercury in these fish probably explain why consumption of ocean fish is not associated with mercury intoxication [135]. In almost all species of oceanic fish tested the amount of selenium exceeded that of mercury on a molar basis [136, 137]. Selenium was first considered to be a toxin, which it is when the dose is sufficiently high. Its essential antioxidant function was discovered in 1957. It is now considered an essential trace element, with a recommended daily allowance for adults of 55 $\mu\text{g/day}$. It is found in virtually

all commercial vitamin supplements. Selenium has been shown to protect against mercury toxicity in all animal species studied. Although historically the toxicity of mercury has been attributed to its great affinity to bond to sulfur-containing amino acids in protein, the binding affinity of mercury to selenium (to form inert mercury selenide) is a million times stronger than mercury's binding affinity to sulfur. In effect then, selenium can prevent mercury from causing health problems by sequestering mercury as mercury selenide. Alternatively, however, too much mercury in the diet can actually cause a selenium deficiency.

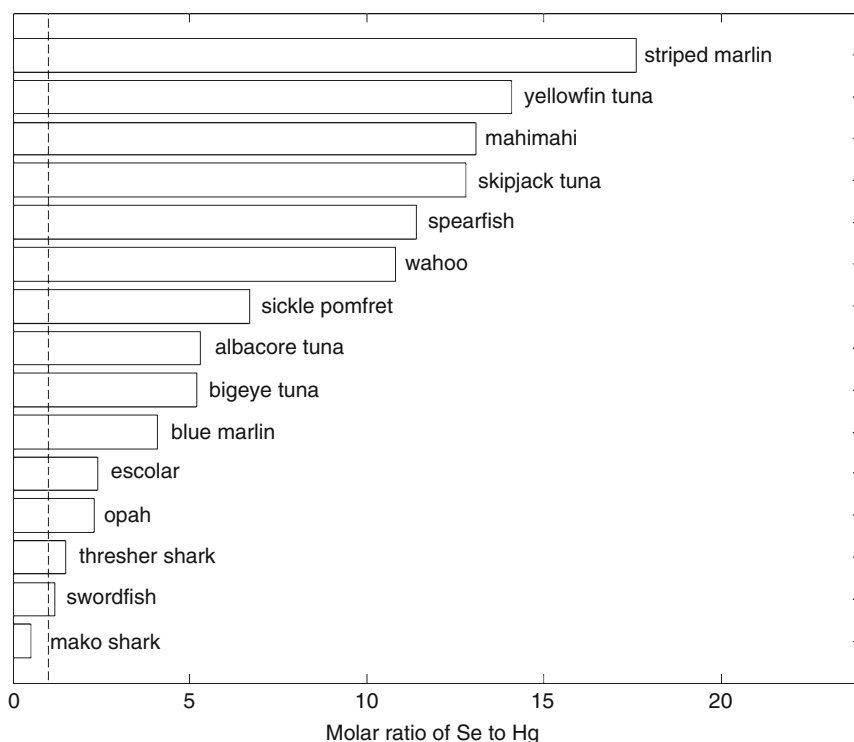
The conclusion then is that fish are unsafe to eat only when mercury concentrations in the fish are higher than the selenium concentrations [137]. In such cases the adverse health effects may reflect a combination of the directly toxic effects of the mercury and/or a selenium deficiency caused by the fact that selenium and mercury sequester one another. The only cases where mercury to selenium ratios exceed one is in some sharks and pilot whales. Selenium is necessary for cellular function in most animals. It is required for more than 25 enzymes with important functions [138, 139]. The ability of selenium to effectively detoxify metals such as mercury was first reported in 1967 [140]. The ability of selenium to decrease mercury toxicity has been established in all species examined to date [141, 142]. The high binding affinity between mercury and selenium [143] is very likely responsible for the ability of selenium to sequester and therefore detoxify mercury. As long as the ratio of selenium to mercury in the diet is sufficiently high, the selenium can sequester the mercury and effectively render the mercury harmless [136, 144]. Molar concentrations of selenium in fish are essential factors in evaluating risks associated with dietary mercury exposure. If the selenium level is higher in the fish than the mercury level, the fish is considered safe to eat [137]. The molar ratio of selenium to mercury is quite high in the muscle of most commercially important ocean fish [137, 145–148]. Pelagic oceanic fish are rich in selenium relative to mercury. Such fish appear more likely to prevent mercury toxicity than to cause it. The old thinking was that mercury was toxic by itself; the new thinking is that selenium and mercury sequester one another. Many of the symptomologies that were previously attributed to

mercury toxicity are being reexamined as possible cases of selenium deficiency caused by mercury's role in sequestering selenium.

Future Directions

The prognoses for CFP and methylmercury are rather different. CFP is caused by a toxin that is naturally produced by certain species of marine dinoflagellates and passed up the food chain. Human activities appear to be largely unrelated to production of the gambiertoxins that are subsequently converted to various congeners of CTX. At the present time the best defense against CFP appears to be refraining from eating certain kinds of fish (e.g., barracuda) that have historically been associated with CFP. Based on extensive surveys in areas where CFP occurs, this policy would amount to erring on the side of safety but would apparently result in many harmless and nutritious fish being deleted from the menu. A preferable solution would be the development of a simple and inexpensive test to determine whether a fish contains CTX. Unfortunately, no such test currently exists, and because there are reported to be literally dozens of congeners of CTX, it is unclear that a single test could provide a reliable yes/no answer to the question. Ultimately an antibody-based assay may solve the problem, but at least at this point in time, development of such an assay is not imminent.

In the case of methylmercury, it is fair to say that very significant progress has been made since the discovery of Minamata Disease. Global production of mercury has declined by about 70% since 1970, a pattern that in no small part reflects recognition of the toxicity of mercury (especially methylmercury) and the efforts of government agencies to regulate mercury use and discharges and of industry to identify substitutes for mercury in many of its earlier applications and to reuse and recycle in cases where no substitutes exist. Probably the most important ongoing development is the controversy surrounding the health effects associated with consumption of fish and shellfish. With respect to this issue, public education is very important. The fact is that most fish and shellfish contain very little mercury. It is therefore straightforward to obtain the nutritional benefits of eating fish and shellfish without any risk from mercury intoxication.



Bioaccumulation/Biomagnifications in Food Chains. Figure 5

Molar ratio of selenium to mercury in fish from the central North Pacific near Hawaii. Dashed line corresponds to a molar ratio of 1.0 (Data from Kaneko and Ralston [137])

Remarkably, almost all fish reported to contain more than trace amounts of mercury also contain substantially more selenium than mercury (Fig. 5), the result being that consumption of those fish may actually safeguard the consumer against mercury intoxication from other sources of exposure as opposed to being a threat to human health. The exceptions to this last statement include pilot whales and mako sharks, which are not in the creel of most fishermen, not on the menu at many restaurants, and not on the dinner table of most people.

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Biochar, Tool for Climate Change Mitigation and Soil Management

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Glossary

Biochar The porous carbonaceous solid produced by thermochemical conversion of organic materials in an oxygen-depleted atmosphere which has physiochemical properties suitable for the safe and long-term storage of carbon in the environment and, potentially, soil improvement.

Black carbon The continuum of solid combustion products ranging from slightly charred degradable biomass to highly condensed, refractory soot. All components of this continuum are high in carbon content, chemically heterogeneous, and dominated by aromatic structures.

Carbon (dioxide) equivalent Common measure of global warming potential constructed by converting the emissions of the six greenhouse gases under the Kyoto Protocol of the UNFCCC into the equivalent radiative forcing units of CO₂. CO₂, N₂O, and CH₄ are the relevant Kyoto gases to be considered in evaluating biochar.

Carbon abatement (CA) The net effect of changes in greenhouse gas fluxes that result from the production and application of biochar. This can include any or all of the following: carbon stored in biochar; CO₂ equivalent emissions released during pyrolysis; offset CO₂ equivalent emissions arising from avoided fossil fuel combustion; offset CO₂ equivalent emissions from reduced chemical inputs to agriculture; change in nitrous oxide and/or methane flux through biochar addition to soils; change in carbon in soil organic matter due to biochar addition; and offset CO₂ equivalent emissions from changed operations in the field. Which of these components is included will be specified in the text.

Carbon credit Any mechanism for allocating an economic value to a unit of carbon (dioxide) abatement. The most common units are EU Allowances (EUAs) (under the EU ETS), Emission Reduction Units (ERUs) (Joint Implementation, UNFCCC), Certified Emission Reductions (CERs) (Clean Development Mechanism, UNFCCC), and Verified Emission Reductions (VERs) (voluntary carbon market).

Carbon stability factor (CSF) The proportion of the total carbon in freshly produced biochar which remains fixed as recalcitrant carbon over a defined

time period (10, 100 years, etc., as defined). A CSF of 0.75 means that 75% of the carbon in the fresh biochar remains as recalcitrant carbon over the defined time horizon, and that 25% of the carbon has been converted into CO₂.

Charcoal The solid product of natural fire and traditional biomass conversion under partially pyrolytic conditions without yielding bioenergy coproducts.

Mean residence time (MRT) Inverse of decay rate, this is the average time for which carbon in new biochar remains present in a recalcitrant form.

Net primary productivity (NPP) A measure of plant growth and the additional CO₂ fixed and stored into plant biomass over a period of, for example, 1 year; technically, it is calculated as the balance between net photosynthesis and plant (dark) respiration.

Pyrolysis-biochar system (PBS) A combination of a specified pyrolysis technology, transport, distribution and storage infrastructure and application of biochar.

Recalcitrant carbon Aromatic carbon which is resistant to chemical or biological oxidation and subsequent conversion to CO₂.

Terra preta Literally “dark earth,” these are localized soils, intensively studied, whose dark color appears to result from historic and prolonged management with charcoal, probably for the enhancement of agricultural productivity in and around the Amazon Basin.

Definition of the Subject

Biochar is the solid remains of any organic material that has been heated to at least 350°C in a zero-oxygen or oxygen-limited environment, which is intended to be mixed with soils. If the solid remains are not suitable for addition to soils, or will be burned as a fuel or used as an aggregate in construction, it is defined as char not biochar. There is a very wide range of potential biochar feedstocks, e.g., wood waste, timber, agricultural residues and wastes (straws, bagasse, manure, husks, shells, fibers, etc.), leaves, food wastes, paper and sewage sludge, green waste, distiller's grain, and many others. Pyrolysis is usually the technology of choice for

producing biochar, though biomass gasification also produces smaller char yields. Syngas and pyrolytic bio-liquids, which have a potential use as energy carriers, are produced alongside biochar.

The strongest evidence for the beneficial effects of char additions to soils arises from the *terra preta* soils of the northern Amazon, where dark, highly fertile soils with very high levels of both stable (char) carbon and organic carbon were established and remain today [1]. Char was also added historically to soils in parts of northern Europe (including Netherlands, NW Germany, and Belgium) [2]. Chars have been, and are currently being used as soil amendments in Japan and West Africa.

The contemporary interest in biochar started in the early part of the twenty-first century and arises from the bringing together of the potential benefits for soils and agriculture with the carbon storage or sequestration opportunity afforded by recalcitrant, stabilized aromatic carbon. Biochar production and deployment has the potential to do one or more of the following:

- Reduce atmospheric greenhouse gas concentrations through CO₂ removal and avoided greenhouse gas emissions (perhaps on a gigaton carbon abatement scale)
- Improve the structure, properties, and “health” of soils
- Increase crop productivity
- Provide energy (e.g., electricity from syngas, heat from syngas, power from liquid fuels)
- Safely dispose of certain waste materials with potentially useful recovered by-products
- Absorb pollutants and contaminants and reduce nitrate leaching to water courses
- Suppress soil emissions of nitrous oxide and methane

Biochar is one of only a few strategies for actually removing CO₂ from the atmosphere (in addition to reducing atmospheric emissions where the use of fossil fuels is substituted for). While this feature may not currently be a top priority, it will become increasingly important in the decades to come, as it is almost inevitable that atmospheric CO₂ concentrations are now set to exceed what is commonly regarded as a safe level

(400–450 ppm). Biochar has consequently been termed ageo-engineering option, though it is a debatable point (See [Box 1](#)).

Introduction

Contemporary biochar research originates from several different sources: (a) research on *terra preta* soils from Amazonia dating back to the middle part of the twentieth century and earlier (e.g., the pioneering work of Sombroek) [3]; (b) research on the effects of charcoal on soils and plants, with initial contributions from the early- to mid-twentieth and more significant efforts in Japan in the 1970s and 1980s; (c) research on the properties and cycling of naturally occurring black carbon and charcoal; and (d) engineering RD&D on pyrolysis and gasification. The idea of the long-term storage of carbon in a stabilized form as found in charcoal (aromatic benzene-ring-type structures) was first proposed by Seifritz in 1993 [4], though his vision was storage in suitable land formations (such as valleys) rather than on agricultural land. This proposal was somewhat ahead of its time, and it was not until the first half-decade of the twenty-first century that the climate-change agenda provided a way of bringing the quite disparate areas of soil science, agronomy, environmental science, and engineering together under the banner of “biochar”. Johannes Lehmann and Peter Read were important in making this conceptual linkage. A series of meetings took place in 2006 to 2008 which began to define and consolidate the emergent biochar community of researchers, practitioners, policy makers and entrepreneurs, including the first three meetings of the International Biochar Initiative (2007, Australia; 2008, UK; 2010, Brazil). In 2009, the first dedicated biochar book was published, edited by Lehmann and Joseph [5], and a series of national and regional meetings were held in 2009–2011, including in the USA, UK, Australia, China, Malaysia, and Brazil. Dedicated biochar research centers have now been established in the USA, Germany, New Zealand, and the UK, while existing departments, laboratories, or field stations in the disciplines of soil science, pyrolysis engineering and agronomy are increasingly turning their attention to biochar RD&D. Writing in 2010/2011, biochar has now become a distinct cross-disciplinary field of enquiry, a remarkable

achievement given that the word was not even in circulation until the mid-2000s. Several comprehensive reviews of the biochar field were published in 2009 and 2010, and these can be read alongside the current chapter [2, 6, 7].

In this chapter, biochar is reviewed from the perspective of climate change, biomass and bioenergy resources, soils and agronomy. Biochar intersects all these issues and has to be evaluated against the dominant and emerging designs and options for solving problems and creating opportunities in those separate domains. As a multipurpose product and/or as an element of a multifunctional system, the different potential functions and purposes of biochar need to be dissected and analyzed. In section “[What Is Biochar and How Can It Contribute To Carbon Mitigation?](#),” biochar is defined, and the key arguments as to why it might be useful in carbon mitigation are presented. In section “[Biochar Production](#),” the main ways in which biochar can be produced are covered, briefly describing the key technological issues and challenges. Section “[Properties of Biochar](#)” covers some of the properties of biochar. Section “[Carbon Mitigation Potential of Alternate Production Technologies](#)” provides an account of the energy and carbon balance of the pyrolysis process that is at the core of biochar as a carbon abatement strategy. Section “[Evaluating Carbon Abatement from Biochar](#)” extends this to an analysis of carbon abatement across the biomass-bioenergy-biochar lifecycle and addresses three crucial questions.

- How much potential carbon abatement might arise from biochar globally?
- How efficient is carbon abatement through biochar compared to alternative use of the same organic matter across the life-cycle of the system?
- How cost efficient is carbon abatement through biochar?

Section “[What Are the Impacts of Biochar on Soil](#)” is a detailed analysis of the impacts of biochar in soils. In section “[Conclusion: Evaluating the Sustainability of Pyrolysis-Biochar Systems](#),” some preliminary conclusions regarding biochar and its wider sustainability are presented. Finally, in section “[Future Directions for Research, Development and Demonstration](#),” some key research needs and future directions are considered.

What Is Biochar and How Can It Contribute to Carbon Mitigation?

We define biochar as the porous carbonaceous solid produced by the thermochemical conversion of organic materials in an oxygen-depleted atmosphere and which has physiochemical properties suitable for the safe and long-term storage of carbon in the environment and, potentially, soil improvement. This definition is deliberately flexible and refers to both the production of biochar and its application.

Combustion of organic matter will take place if there is too much oxygen present during thermal conversion, and the resulting solid will be ash which typically contains just a few percent of carbon by mass, in addition to compounds and elements (phosphorus, potassium, other metals, etc.). With a low-level of introduced oxygen and thermal treatment of the organic matter, gasification may take place, during which volatile organic compounds are generated and released as vapor. This energy-rich synthesis gas (“syngas”) can be cleaned and used for electricity-generation.

Pyrolysis occurs where the organic matter is subject to heat in the absence of any introduced oxygen and yields about a third of the feedstock as char (by weight), while gasification produces up to 10% char by weight. Charcoal is a type of char that has been produced (intentionally or otherwise) from wood for millennia, and much of our knowledge of biochar derives from the study of charcoal. Charcoal has also been used in soil-management practices for millennia and has well-documented benefits. While these are best observed in tropical environments – most famously in the *terra preta* soils of the Amazon – they have also been observed in temperate and semi-tropical regions.

It would be a mistake to equate biochar and charcoal however, since biochar represents a much wider group of materials which are likely to have far more variable properties than charcoal. Biochar comprises stabilized plant material in which carbon is stored mainly in a chemically recalcitrant form which will not significantly degrade through microbial activity or chemical reaction in the environment. It is this recalcitrance which is of interest from a carbon mitigation perspective since the carbon is thereby unavailable to microorganisms and does not return to the atmosphere as carbon dioxide (CO₂). But how long does

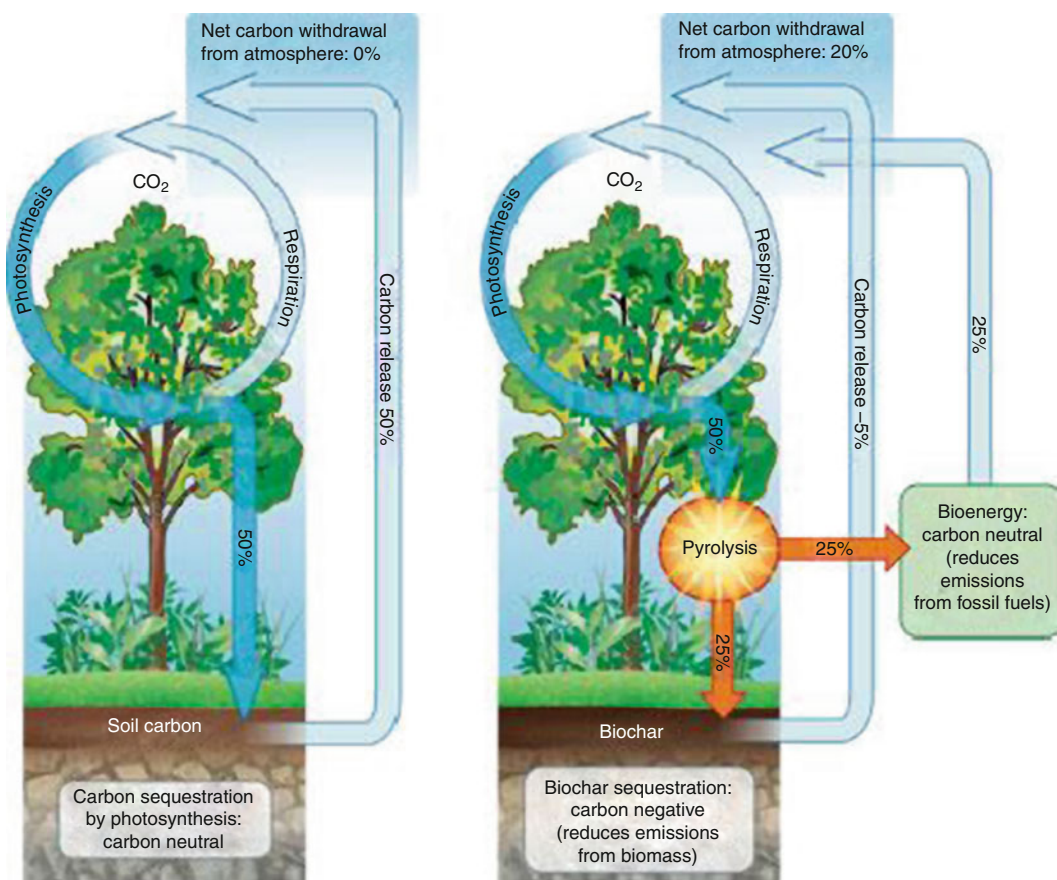
carbon remain fixed in biochar? The mean residence time (MRT, the inverse of the decay rate) is the average time for which carbon in new biochar remains present in a stabilized aromatic form. The MRT of charcoal and analogous material is in the order of millennia [8]. Biochar may therefore provide an effective long-term store of carbon in soil and thus offer a potential abatement option for anthropogenic carbon emissions [9].

Stabilization of Plant-Captured Carbon

Annually, plants draw down 15–20 times the amount of CO₂ emitted from fossil fuels (7.5 Gt C year⁻¹), up to 20% of the entire atmospheric pool. About half of this is returned immediately to the atmosphere through plant respiration, but about 60 Gt C year⁻¹ [10] is invested in new plant growth (about 45% of plant biomass is carbon) and contributes to net primary productivity (NPP). Since plant biomass is relatively constant globally, the magnitude of new plant growth must be approximately matched by harvest, litterfall, exudation by roots, etc. The annual CO₂ release from decomposition of these products by natural pathways and human cycling of plant-derived materials and products roughly equals NPP. The annual return of carbon to the atmosphere from the decomposition of all prior cohorts of plant material is thus approximately equal to NPP.

Intercepting and stabilizing plant-biomass production reduces the return of carbon to the atmosphere, with a relative reduction in atmospheric CO₂ (see Fig. 1). This reduction can be quite immediate if the default rate of decomposition is months to years, as it is for the dominant portion of biomass returned to soil in managed (agricultural and forest) ecosystems. Controlled charring (pyrolysis) can convert up to half of the carbon in plant biomass into chemical forms that are recalcitrant and, in principle, managed soils have a capacity to store pyrolyzed biomass at a rate significant in terms of emissions of carbon from fossil fuel.

The conversion of carbon in plant biomass to charcoal during natural fire is only about 1–5%, but the high level of stability established for such material in soil, which is generally a highly active biological medium, leads to expectation for similar stability in deliberately produced biochar. Biochar, deployed as a “carbon-negative” technology at the scale of 1 Gt C year⁻¹, would



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 1

Schematic illustrating the pyrolysis-biochar concept [9] (With permission from Nature Publishing)

be equivalent to expanding the natural cycle of fire-derived charcoal storage in geographic terms and increasing its global magnitude by a factor of 4–20 [11].

Methane (CH_4) and nitrous oxide (N_2O) are the second- and third-largest contributors to radiative forcing of climate change after CO_2 . Soil is a key source of both gases, which are emitted through natural microbial processes. The global significance of these processes has increased with agricultural expansion since higher CH_4 emission is associated with flooded soil conditions and with an enhanced nitrogen cycle (increased N_2O emissions) provided by the use of (synthetic) fertilizer, manures, and slurry. Since both CH_4 and N_2O are also associated in part with organic matter decomposition, stabilizing degradable organic matter could have a direct impact on soil-based emissions of these gases. Interventions in the nutrient or water balance of soil through changes in the dynamics of water

in soil, or through the adsorption of nitrogen (as ammonium) may indirectly modify emissions of these gases from the soil.

To be a significant response to climate change, carbon abatement on a scale of millions of tons needs to occur, preferably hundreds of millions of tons. To intercept NPP and produce biochar at this scale presents a practical challenge, but still only involves a small fraction of total plant NPP ($60 \text{ Gt C year}^{-1}$) of which 30% is already calculated to be “co-opted” by humans [12]. Increased efficiency of biomass recovery in managed ecosystems, diversion of biomass from current uses where it has a low value, and utilization of used biomass (organic waste) streams provide three ways in which it might be achieved. The fourth option is to sustainably harvest more biomass, which might be achieved by growing more productive plants, increasing the area of managed land, or adjusting harvesting

regimes. Clearly, demonstrable effects on NPP arising from the deployment of biochar could be factored into such strategies.

Indirect CO₂ Equivalent Impacts

Biochar can improve the pore-size distribution of soils, resulting in an improved retention of plant-available nitrogen in the soil, increasing plant N uptake and fertilizer-use efficiency. This implies lower fertilizer requirement and lower eutrophication risks. If the accumulation of biochar results in beneficial change in pore-size distribution, it would result in a more permanent change than can be achieved through the effects of degradable and thus transient organic matter that can be used to condition soil.

The release of nitrogen by soil microbes from decomposition of crop residues in the low-growth winter period (in temperate regions) is a key source of nitrogen loss to water and the atmosphere. Increasing the use-efficiency of nitrogen in recoverable crop residues is therefore of relevance to eutrophication through leaching, and N₂O emissions.

Changing the abundance or physical position of aerobic space in soil (with respect to loci of microbial activity) has the potential to mitigate CH₄ emission. The emission of N₂O from soil could be suppressed by adsorption of nitrogen in the form of ammonium (NH₄⁺). Emissions of both CH₄ and N₂O are notoriously variable both temporally and spatially, and are also sensitive to soil pH. However, these mechanisms may be relevant in the suppression of CH₄ and N₂O by biochar observed at certain locations, or under certain controlled conditions [13].

The Haber–Bosch process used to fix atmospheric nitrogen into solid soluble (ammonium) form is an energy intensive process that accounts for about 40% GHG emissions associated with arable agriculture. Typical use-efficiency for fertilizer nitrogen globally is 30–50% [14] attributable to leaching, immobilization and gaseous loss, and leaching. Technologies that improve the management of these processes through the soil can therefore offer an indirect gain in agricultural carbon-equivalent balance.

Liming of agricultural soil also transfers carbon from the geological pool to the atmosphere through production (calcining of limestone) and subsequent

neutralization in the soil [15, 16]. The alkalinity typical of biochar can potentially substitute for the use of lime in the management of soil pH without emission of CO₂ [13].

Reliable and secure storage for annual and large cumulative amounts of biochar would have to be available, and while simple burial (for example, in landfill or disused mines) has been considered [4], these possibilities would be limited, costly and potentially dangerous. The broader land surface, and in particular soils that are already actively managed, may therefore provide the required capacity for a large and enduring strategy for storing carbon in biochar [17]. The key assumptions are that the estimates for stability of charcoal made so far are typical and accurate, that biochar from modern pyrolysis technologies using more diverse feedstock exhibits broadly similar levels of stability as natural charcoal, and that appropriate feedstocks can be provided sustainably and without adverse environmental or sociopolitical impacts.

Box 1: Is Biochar Geoengineering?

Geoengineering has been defined as the “deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change” [18]. Biochar is regarded as a form of geoengineering by the Royal Society of London, along with afforestation and associated removal of wood for long-term applications and a range of physiochemical methods, including direct air capture, ocean fertilization, ocean alkalinity enhancement, etc. This is because, at a large enough scale, biochar could have a noticeable influence upon the global carbon cycle. Yet, there are reasons why using the moniker geoengineering for biochar is misleading. Firstly, biochar might be a small-scale intervention. Secondly, biochar is not solely concerned with moderating global warming, and there will be instances where its main function is for agronomic purposes and soil improvement, water retention, leachate reduction, or treating contaminated land. Evaluating such projects as geoengineering could be misleading and result in unhelpful comparisons with very different technologies. In many cases, better comparisons can be made between the use of agricultural and organic residues and wastes for composting, incineration, gasification, second generation fermentation, anaerobic digestion, and biochar production.

Biochar Production

Processes

There are several processes which can be used to produce biochar, pyrolysis being the most common. Pyrolysis is a thermochemical decomposition process in which organic material is converted into a carbon-rich solid and volatile matter by heating in the absence of oxygen [19]. The solid product, char or biochar, is generally of high carbon content and may contain around half the total carbon of the original organic matter. The volatiles can be partly condensed to give a liquid fraction leaving a mixture of so-called “non-condensable” gases. Each of the three product streams from pyrolysis – solid, liquid, and gas – can have properties and uses that provide value from the process. There are two main classes of pyrolysis process as well as a number of other more or less related technologies that may be considered for biochar production.

Fast pyrolysis is characterized by high heating rates and short vapor residence times. This generally requires a feedstock prepared as small particle sizes, and a reactor design that removes the vapors quickly from the presence of the hot solids, typically at around 500°C, leading to high yields of liquid products with low char yields. There are a number of established commercial processes (as well as many R&D examples) where the target products are liquids – bio-oils – although biochar from such processes has also been studied [20]. The area of bio-oil from fast pyrolysis has been extensively reviewed [21, 22].

Of more interest for biochar production is slow pyrolysis, which can be divided into traditional charcoal making and more modern processes. It is characterized by slower heating rates, relatively long solid and vapor residence times and usually a lower temperature than fast pyrolysis, around typically 400°C. The target product is generally the char, but this will always be accompanied by liquid and gas products, although these are not always recovered.

Traditional processes using pits, mounds, or kilns, generally involve some direct combustion of the biomass, usually wood, as heat source in the kiln, which reduces the char yield. Liquid and gas products are often not collected but escape as smoke. As well as particulates and carbon dioxide, other greenhouse gases such as methane may be emitted, as well as

other hydrocarbons, and amines, leading to a net positive radiative forcing effect even if the biochar product is used for carbon storage [24]. Hence, traditional charcoal-making techniques are not generally compatible with the objectives of pyrolysis-biochar systems (PBS) for carbon abatement.

Industrial-scale charcoal-making processes, using large retorts operated in batch or continuous modes, achieve higher char yields and avoid most of the issues of emissions by allowing recovery of organic liquid products and recirculation of combustible gases to provide process heat, either internally or externally [26]. Other developments have led to slow pyrolysis technologies which are of most interest for biochar production. These are generally based on a horizontal tubular kiln design, where the biomass is moved at a controlled rate through the kiln and include agitated drum kilns, rotary kilns, and screw pyrolyzers [27], as well as some gravity-driven designs. In several cases, these have been adapted for biomass pyrolysis from original uses such as the coking of coal with production of “town gas” or the extraction of hydrocarbons from oil shale. Although some of these technologies have well-established commercial applications, production of biochar is not yet one of them, and only limited reviews are available [27, 28]. Other technologies that may be considered for biochar production include flash pyrolysis (cf. fast pyrolysis but shorter residence times), intermediate pyrolysis (cf. slow pyrolysis with improved heat transfer, allowing faster throughput), flash carbonization (partial combustion in pressurized reactor), gasification (partial combustion in a gas flow), and hydrothermal carbonization (aqueous process at high temperature and pressure with catalysis) [28]. Typical values and reported ranges for key process variables and product yields of slow, intermediate, and fast pyrolysis processes are shown in Table 1 [28]).

Products

Composition of the three typical product streams from pyrolysis processes, solids, liquids, and gases, will vary with feedstock, process design, and conditions but can be generalized as follows. The solid product, char or biochar, has a varying carbon content, typically ranging from 60 to 90% [29]. In terms of proximate analysis, the char consists of four major components; fixed

Biochar, Tool for Climate Change Mitigation and Soil Management. Table 1 Scope of pyrolysis process control and yield ranges

Process	Slow pyrolysis	Intermediate pyrolysis	Fast pyrolysis
<i>Temperature</i> (in degrees centigrade)			
Range	250–750	320–500	400–750
Typical	350–400	350–450	450–550
<i>Time</i>			
Range	Min-days	1–15 min	ms-s
Typical	2–30 min	4 min	1–5 s
<i>Yields</i> (% oven dry weight)			
<i>Char</i>			
Range	2–60	19–73	0–50
Typical	25–35	30–40	10–25
<i>Liquid</i>			
Range	0–60	18–60	10–80
Typical	20–50	35–45	50–70
<i>Gas</i>			
Range	0–60	9–32	5–60
Typical	20–50	20–30	10–30

Based on review of over 30 literature sources [28]

carbon, volatile carbon, ash and moisture. Energy contents of biochar range typically 20–30 MJ kg⁻¹ (Higher Heating Value (HHV), [28]).

Liquid products from biomass pyrolysis are frequently termed bio-oil. However, this is a somewhat confusing term as the organic liquid product is generally hydrophilic, containing many oxygenated compounds, and is present sometimes as a single aqueous phase and sometimes phase-separated, together with water produced in the pyrolysis reaction or remaining from the feedstock [19]. Energy contents of bio-oils range typically from 15 to 30 MJ kg⁻¹ (HHV, [28]), but figures quoted may be given after a degree of purification. The gas product is termed synthesis gas, shortened to syngas. It is typically a mixture of carbon dioxide (9–55% by volume), carbon monoxide (16–51%), hydrogen (2–43%), methane (4–11%), and small amounts of higher hydrocarbons [28]. Literature values for syngas energy content ranges are sparse,

partly due to varying composition during processing and the presence of inert gas, with available values ranging from 8 to 15 MJ kg⁻¹ (HHV, [28]).

Effect of Feedstock and Process Variables

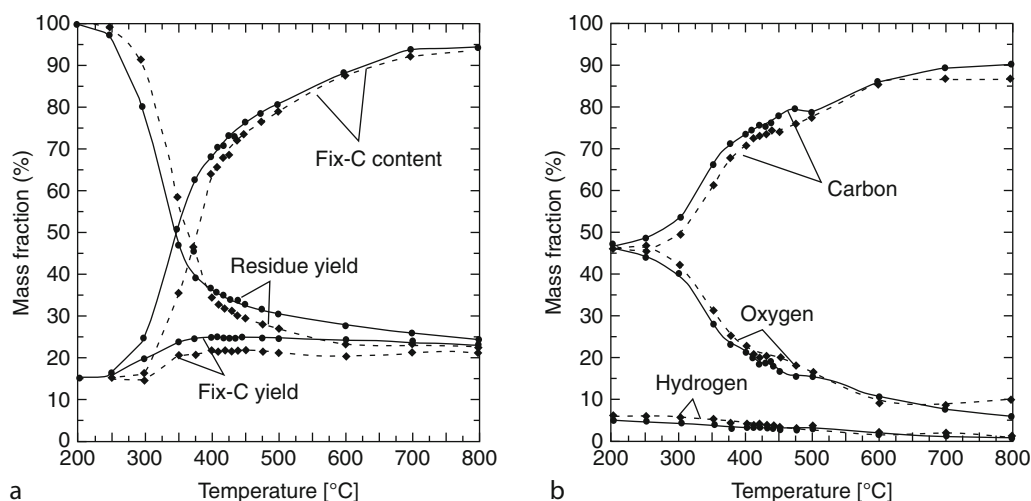
The nature and preparation of pyrolysis feedstocks as well as the process conditions used influence both the composition and distribution of products. The main effects are caused by feedstock properties, the gas environment, and temperature control; and are summarized here for slow pyrolysis [26].

High lignin biomass will tend to give higher char yields, with other components leading to more liquid and gas products. Minerals present in the ash can have a catalytic effect by increasing char yields in some cases. Moisture can have a positive or negative influence on char yields depending on conditions. Larger particle size can increase char yields by restricting vapor disengagement and increasing the scope for secondary, char-forming reactions.

Factors affecting the gas environment that lead to a longer contact time between hot solids (feedstock or char) and primary vapor products lead to increased char yields resulting from secondary char-forming reactions at the hot surface. These factors include particle size, heating rate, and gas flow rate; increased pressure has a similar effect.

Temperature control is one of the most important operational variable, particularly peak temperature. Higher peak temperatures lead to lower char yields and higher liquid yields. For instance, a typical biomass pyrolysis might yield 38% biochar by weight on a dry basis at 350°C, but only 27% when heated at 550°C [30]. Heating rates have a smaller and inconsistent effect on slow pyrolysis. Increasing residence time at peak temperature will lead to lower char yield, but again this is a smaller effect than temperature itself.

Temperature also influences the composition and structure of the biochar formed. Higher temperatures and longer residence times lead to chars with higher concentrations of carbon and fixed carbon (determined by proximate analysis), as more volatile matter is driven off; pore structure and surface area also develop with more severe conditions. Figure 2 shows some of these temperature effects, including the effect on elemental composition of char, in a series of



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 2

Effects of temperature and heating rate on (a) char yield, and (b) carbon, hydrogen, and oxygen content of beech chars. Solid and dashed lines are 2°C and 10°C min⁻¹ heating, respectively [26] (Reproduced with permission from the American Chemical Society)

experiments with pyrolysed beech-wood [26]. Note that the complementary decrease in char (residue) yield and increase in fixed-carbon content at successively higher temperatures leads to a plateau in the fixed-carbon yield above about 400°C in this example. The relationship between fixed-carbon and soil-carbon stability is not yet clear [30].

Energy Balance

During pyrolysis, components of the biomass feedstock react by different pathways contributing to the complex products observed. Individual reactions may be endo- or exothermic and the combined process may also be endo- or exothermic depending on conditions of reaction [26]. Even when conditions favor exothermic reactions, initial heating to achieve onset temperature is required. Heat input may be provided by an external heat source, by partial oxidation of the feedstock, or by recycling and combustion of one of the product streams.

In conceptual designs for pyrolysis-biochar systems, the syngas, bio-oil, or combined gas/vapor stream are the preferred energy sources for the process. Data for process energy is not generally available in the literature but estimates suggest a requirement in the order of 10% of the energy value of the dry feedstock.

In most cases, the product distributions will leave an excess of energy in the gas and/or liquid streams which can be used for electrical generation or exported heat, but note that the higher the biochar yield obtained, the lower this excess energy will be, a significant point for the economics of the process.

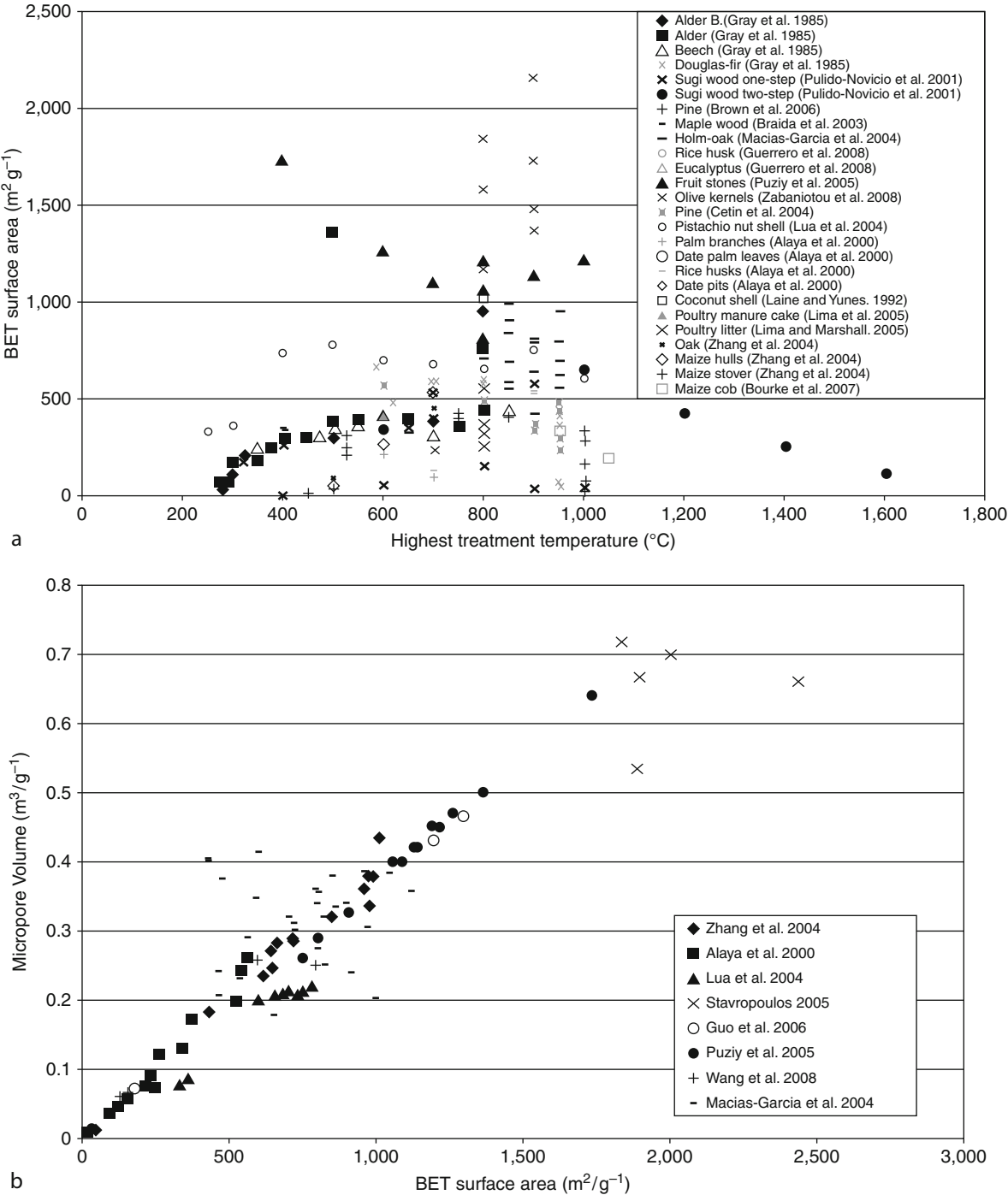
Properties of Biochar

Cation Exchange Capacity

Biochar has the capacity to exchange cations (e.g., ammonium, NH₄⁺) with soil solution, and thereby store crop nutrients. The extent of this cation exchange capacity (CEC) is effectively absent at very low pH and increases at higher pH [32]. Experimental results show that the CEC of fresh biochar is typically low but increases with time as the biochar ages in the presence of oxygen and water [33–35].

Specific Surface Area

Biochar has a very high specific surface area (SSA) of several hundred m² g⁻¹ to a thousand m² g⁻¹ (Fig. 3). The main parameters influencing SSA are pyrolysis temperature, heating rate, residence time, and presence of active reagents (e.g., steam, CO₂, O₂, etc.). Figure 3a shows that the total surface area of biochar from most



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 3
Biochar surface area (a) plotted against treatment temperature and (b) its apparent relationship with micropore volume [36] (Reproduced with permission from Earthscan Ltd.)

feedstocks tends to increase with increasing pyrolysis temperature. This is mainly due to the development of micropores that are responsible for most of the surface area, see Fig. 3b.

At present, it is not clear whether the additional surface area presented by micropores plays as important role in soils as macropores and, therefore, whether it is beneficial to produce a biochar with very high SSA. It may be possible to produce biochar with high SSA in the macropore range. However, the physical structure of biochar tends to be defined by the starting material, so fine milling or compaction of the feedstock before pyrolysis is necessary to achieve a well-defined macroporous product [37].

Contaminants

There are two main potential sources of contamination in biochar: feedstock and the conversion process. Depending on the origin and nature of the pyrolysis feedstock, biochar may contain contaminants such as heavy metals (potential toxic elements, PTEs) and organic compounds. Some of these compounds will undergo changes in the conversion process and might be destroyed (or converted to benign compounds), while others will remain unchanged or give rise to potentially harmful substances. In addition to the contaminants introduced in the feedstock, some contaminants can also be formed in the conversion (pyrolysis) process. These include polycyclic aromatic hydrocarbons (PAH) and potentially, in some cases, dioxins. Additionally, the physical form of pyrolysis products may present a direct health risk, and increase or decrease the risk posed by elements, compounds, or crystalline material both in feedstock or formed during pyrolysis.

Heavy Metals

Heavy metals present in the feedstock (e.g., MSW, sewage sludge, treated wood, etc.) are most likely to remain and concentrate in the biochar (with lower char yields, resulting in higher concentration of PTEs) [38–42]. Therefore, careful selection and analysis of feedstock is necessary to avoid contamination of biochar with increased levels of heavy metals. Heavy metals are stable materials and therefore retained (conserved) during volatilization of associated organic molecules. The majority of metals will therefore be present as ash within

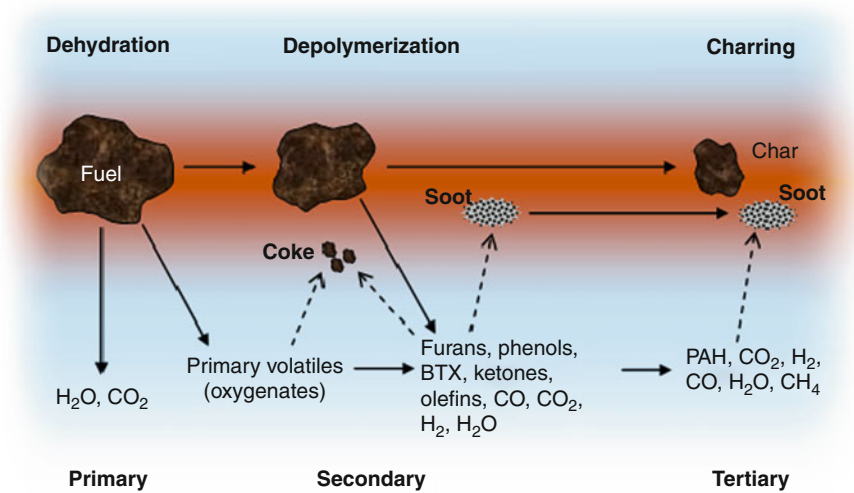
biochar (together with nutrient elements such as phosphorus and potassium). It may thus be possible to manipulate contaminant loadings through selective removal of ash [43]. Alternatively, it has been shown that high-temperature pyrolysis can release heavy metals from the solid product, thereby yielding char with lower loading of these contaminants [44].

Polycyclic Aromatic Hydrocarbons (PAHs)

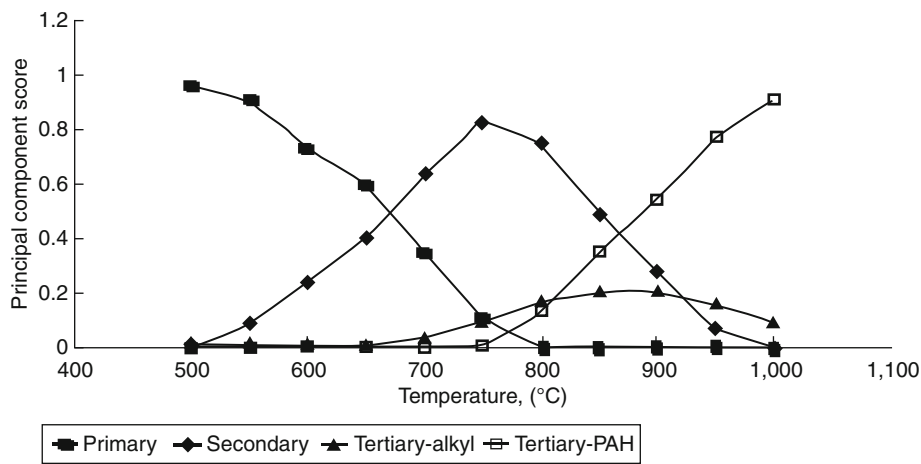
PAHs can be formed from any carbonaceous feedstock. The major chemical pathways for (PAHs) formation in the pyrolysis process are the high-temperature secondary and tertiary pyrolysis reactions (homogeneous and heterogeneous), as shown in Figs. 4 and 5 [163]. The formation of these tertiary pyrolysis products increases with the pyrolysis severity (i.e., temperature and residence time) and becomes significant at temperatures around 750°C.

However, there exists also a second, less explored route for PAH formation. Evolution of PAHs from the solid substrate has been reported in the temperature range of 400–600°C [43, 45]. This pathway yields predominantly lower molecular-weight PAHs, although higher molecular-weight PAHs, such as benzo(a)pyrene, are also formed [45–47].

As the optimum temperature for biochar production is likely to lie in the region 450–550°C, in a well-controlled system (without hotspots), formation of PAH would proceed mainly by the evolution from solid substrates. PAH formation in the gas phase should be minimal due to the low pyrolysis temperature. Data on PAH content in pyrolysis char is scarce but indicate that the concentration and composition of PAHs in biochar are feedstock dependent [49]. Other data show that PAH concentrations in biochar produced from untreated biomass at temperatures of up to 600°C are considerably lower than those in urban soils in England, in the order of 10–100 mg kg⁻¹ [50]. Biochar produced from chemically treated biomass is liable to contain considerably higher levels of PAHs than biochar from virgin feedstock due to the possibility of indigenous PAHs apparent in a study of biochar produced from railway sleepers previously treated with tar and creosote [49]. Available published data on the concentration of benzo(a)pyrene, one of the most toxic PAH compounds, is shown in Table 2.



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 4
Progress of fuel particle pyrolysis [51]



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 5
The distribution of the four “tar” component classes as a function of temperature with 0.3 s gas-phase residence time [48]
(Reproduced with permission from NREL)

Biochar, Tool for Climate Change Mitigation and Soil Management. Table 2 Concentration of benzo(a)pyrene in biochar and UK soil [49, 50]

Benz[a]pyrene content ($\mu g\ kg^{-1}$)				
Birch char	Pine char	Pine sleeper char	Urban soil (England)	Rural soil (England)
310	570	4,040	714	67

Dioxins

Dioxins, unlike PAHs (which can be formed from any carbonaceous feedstock) require chlorine for their formation. Consequently, only biochar produced from feedstock containing significant amounts of chlorine (e.g. halogenated plastics) could be prone to generation of dioxins under certain conditions. The dioxin

formation process is heavily dependent on the temperature history of the pyrolysis products, and relatively high temperatures (around 750°C) are required for the formation of dioxin precursors (chlorinated benzenes and phenols). Therefore, it is unlikely that biochar produced by pyrolysis at temperatures between 450–550°C would contain dioxins in significant amounts even when produced from feedstock containing chlorine, despite the fact that dioxins can be formed from their precursors in this temperature range. The only exception would be biochar produced from feedstock already contaminated by dioxins or dioxin precursors.

Stability

The stability of biochar is one of its key properties as it determines its potential for long-term storage of carbon. However, despite its importance, there is no recognized way of determining stability of biochar. It is very difficult to predict stability of biochar over timescales relevant to carbon sequestration, i.e., centuries to millennia. This difficulty stems from the diversity of processes (biological, chemical, and physical) responsible for biochar degradation in the environment and the wide range of properties biochar from different sources pose. It seems that simple correlation of long-term biochar stability with any particular physical or chemical property of biochar is difficult, and new methods, such as accelerated aging, are being investigated. Preliminary results have shown that high levels of stability can be achieved in a wide range of production conditions [30].

Carbon Mitigation Potential of Alternate Production Technologies

The overall effect of pyrolysis-biochar production on carbon abatement, prior to soil incorporation, can be described as the sum of two main factors: the carbon stored in biochar (related to CO₂ removed from the atmosphere) and the CO₂ emissions avoided through substitution of fossil fuels by combustion of pyrolysis products for energy. In calculating avoided emissions, a baseline case needs to be established for comparison, selection of which can have a large impact on the results. There are three elements for selecting a baseline:

1. *Carbon intensity of displaced fossil fuel energy.* Avoided CO₂ emissions are calculated relative to

the average CO₂ equivalent emissions (including contributions of CH₄ and N₂O) from generation of grid electricity (or that from a specific facility). The carbon dioxide emission factor (CEF) of the grid varies over time with the mix of fuels used. In the UK, it has decreased over recent decades with the trend away from coal toward use of natural gas. Expressed as kg CO₂eq kWh⁻¹ electricity, CEF has fallen from 0.78 in 1990 to 0.55 in 2007 [52]. Given this trend, the UK government recommends using a CEF of 0.43 kgCO₂eq kWh⁻¹ for comparisons when considering renewable electricity development [53]. The actual CEF value, e.g., 0.5 kgCO₂eq kWh⁻¹ in 2008, could also be used. The most appropriate CEF would be employed in a specific case-study context. It will be less for an energy system that is less reliant upon coal and other fossil fuels.

2. *Carbon neutrality or otherwise of biomass system.* Combustion of biomass for energy generation releases c. 99% of plant carbon as CO₂; it is conventionally assumed that the same quantity of biomass is replanted (without incurring any additional greenhouse gas emissions), hence the same quantity of CO₂ is taken up by the growing plants and the system is “carbon-neutral”. Yet, if direct or indirect land-use change is entailed, carbon neutrality cannot be assumed: for instance, change from managed grassland (with c. 80 tC ha⁻¹) to energy-crop cultivation will involve immediate loss of CO₂ due to soil disturbance. Depending upon the energy crop, the equilibrium soil organic carbon content may decrease (e.g., to 45 tC ha⁻¹ in a wheat for bioethanol context) or possibly increase (e.g., by up to 20 tC ha⁻¹ over 20 years in the case of Miscanthus) [54]. It is therefore more accurate to include considerations of land-use change and the feedstock carbon cycle explicitly. Below we calculate the net carbon abatement from PBS assuming biomass replacement (carbon neutrality) and no replacement.
3. *Carbon Stability Factor (CSF) of biochar.* The CSF is defined as the proportion of the total carbon in freshly produced biochar which remains fixed as recalcitrant carbon over a defined time period (see Glossary). As yet, little information exists on the actual CSF of specific biochar samples due to

scientific uncertainties over biochar stability. A further uncertainty is the selection of the appropriate time period over which the stability is measured. Previous studies have used a range of values of the CSF from 0.68 over 100 years [55], 0.8 (time period undefined) [56], 1.0 (time period undefined) [57], 0.75 over 10 years [58], and 1.0 over 10 years [59]. As yet, there is no convention on the definition, measurement, and time horizon for reporting the CSF. To a certain extent, the selection of the time period is subjective and influenced by the decision-makers' preferences. In this review, we have adopted a time period of 100 years which is a compromise between the (multi-) millennial timescale of the climate system and the decadal (and frequently shorter) timescale of commercial and policy decision making. This also follows the convention of assessing Global Warming Potentials (GWP) to compare the radiative forcing of different GHGs over 100 years.

Equation 1 can be used to calculate the net carbon abatement arising from for combustion, PBS, or soil incorporation of biomass:

$$\text{CO}_{2\text{na}} = \text{CO}_{2\text{av}} + \text{CO}_{2\text{fix}} - \text{CO}_{2\text{rel}} \quad (1)$$

where:

$\text{CO}_{2\text{na}}$ is net carbon eq. abatement

$\text{CO}_{2\text{av}}$ is carbon eq. emissions avoided by replacement of fossil fuels

$\text{CO}_{2\text{fix}}$ is carbon eq. fixed in the long-term (100 years)

$\text{CO}_{2\text{rel}}$ is carbon eq. released by the biomass feedstock processing

(All expressed in $\text{tCO}_2\text{eq.t}^{-1}$ feedstock).

Meanwhile:

$$\text{CO}_{2\text{fix}(100)} = \text{BM}_{\text{tot}} \times \text{BC}_{\text{yield}} \times \text{CO}_{2\text{tot}} \times \text{CSF} \quad (2)$$

where:

$\text{CO}_{2\text{fix}(100)}$ is CO_2 eq. fixed over 100 years

BM_{tot} is biomass total dry weight

BC_{yield} is biochar yield (ratio)

$\text{CO}_{2\text{tot}}$ is total CO_2 eq. content of fresh biochar

CSF is carbon stability factor over 100 years

(All expressed in $\text{tCO}_2\text{eq.t}^{-1}$ feedstock).

Data for the example of 1 t of straw is given in Table 3. It can be seen that if combustion is used, 1.65 tCO_2 is released immediately, but there is an avoided emission of 0.66 tCO_2 arising from the substitution of fossil fuels (assuming a CEF of 0.5 $\text{kgCO}_2\text{eq.kWheq}^{-1}$). The net CO_2 emission, assuming that there is no biomass replacement, is therefore c. 1 $\text{tCO}_2 \text{t}^{-1}$ feedstock. If the same 1 t of straw is pyrolysed to produce biochar, the net CO_2 emission is lower at 0.45 $\text{tCO}_2 \text{t}^{-1}$, assuming electricity generation from PBS is feasible. If no electricity cogeneration is possible, the net emission increases to 0.73 $\text{tCO}_2 \text{t}^{-1}$, still lower than combustion (though obviously without the benefit of electricity generation). If full biomass replacement is assumed, biomass combustion and PBS both deliver net carbon abatement, though the biochar option more so.

If the alternative use of the straw is for incorporation into the soil however then the emission of CO_2 arising from decomposition would be slower. At day 1, 1.65 t of CO_2 remains in the biomass, and if we assume an exponential decay with a decay constant of 1.0, then after 4 years the vast majority of the straw has mineralized. Assuming that 5% of the straw biomass is stabilized as long-term soil carbon, then the direct incorporation abates more carbon from day 1 to 6 months. After that time, however, PBS with electricity generation and no biomass replacement abates more carbon, while after 1 year PBS without electricity generation and with no biomass replacement achieves higher carbon abatement than direct incorporation. The analysis is more complicated in the case of biomass replacement and is not attempted here. Clearly, this result is heavily dependent upon the decay function, and constant and slower rates of decomposition would give very different results under which direct incorporation would be more "competitive" in terms of carbon abatement relative to combustion and PBS.

In effect, pyrolysis has an associated "carbon debt" to pay-off due to release of CO_2 during pyrolytic conversion. The time period of this "carbon debt" is sensitive to the time horizon selected for measuring the CSF. If a shorter time horizon is chosen in measuring the CSF, then the carbon debt will appear to be smaller because the PBS CA will be larger, and vice versa. It is therefore important when evaluating options to be clear about what the PBS option is being compared

Biochar, Tool for Climate Change Mitigation and Soil Management. Table 3 Simple calculation of carbon stored and avoided CO₂ emissions arising from pyrolysis-biochar, combustion, and direct field incorporation for one oven dry ton of straw

Indicator	Combustion	Pyrolysis-biochar (with electricity generation)	Pyrolysis-biochar (no electricity generation)	Direct incorporation of straw into field ^a
Starting feedstock mass (t)	1	1	1	1
Carbon content at start (t)	0.45	0.45	0.45	0.45
Carbon content at end (stabilized) (t) ^b	0	0.25	0.25	0 year: 0.45 0.5 year: 0.27 1 year: 0.18 1.5 years: 0.11 2 years: 0.05
Expressed as CO ₂ (t)	0	0.92	0.92	0 years: 1.65 0.5 year: 1.0 1 year: 0.66 1.5 years: 0.40 2 years: 0.18
Calorific value of straw: 13.5 GJ t ⁻¹				
Efficiency of conversion	35%	15%	0%	0%
Delivered energy (GJ t ⁻¹)	4.725	2.025	0	0
Carbon emission factor: 0.5 kg CO ₂ per kWh (2008 electricity mix)				
Delivered energy kWh	1,312.5	562.5	0	0
Avoided CO ₂ emissions (t)	0.656	0.281	0	0
Total CO ₂ abatement per ton feedstock (t) assuming carbon neutrality	0.656	1.2	0.92	
Total CO ₂ abatement per ton feedstock assuming no biomass replacement (t)	−0.994	−0.449	−0.73	0 year: 0.18 0.5 year: −0.48 1 year: −0.81 1.5 years: −1.06 2 years: −1.28

^aAssumes an exponential decay function with a decay constant of 1.0

^bAssumes that 55% of the carbon in the feedstock is stabilized over 100 years

to, what the CSF and time period is, and to use these numbers to calculate the carbon debt of PBS.

A simplified model was developed to calculate net carbon abatement for slow, intermediate and fast pyrolysis [28]. The data required for the model (Table 4) were gathered in a comprehensive literature review complemented by direct communication with relevant experts [36, 58, 60–64]. Model outputs are all expressed on a feedstock dry weight basis. A default value of 33% for electrical conversion efficiency of the

main model output data is assumed but with no use of spare process heat (beyond drying the feedstock). The CEF used is 0.43 kgCO₂eq kWh⁻¹ and the results are shown in Table 5.

Results of the model show that fast pyrolysis may give the highest electrical energy product. This is due to the high liquid (oil) yields from the process, which can then be used for power generation. On the other hand, the electrical energy product is lowest for the slow pyrolysis process, where much of the energy value of

Biochar, Tool for Climate Change Mitigation and Soil Management. Table 4 Data required for the pyrolysis process model

Model inputs	Slow pyrolysis	Intermediate pyrolysis	Fast pyrolysis
<i>Process input</i>			
<i>Biomass</i>			
Carbon content (%)	46	43	50
Energy value (MJ kg ⁻¹)	17*	16	19
<i>Pyrolysis process data</i>			
Gas yield (% input mass)	45	32	13
Liquid yield (% input mass)	15*	35	72
Char yield (% input mass)	40	34	15
Energy loss (% input)	6*	0*	3
Process energy (% input)	10*	10*	10
<i>Primary process output</i>			
<i>Gas</i>			
Energy value (MJ kg ⁻¹)	13.1	11.0	11.5
Carbon content (%)	37.4	30.0*	36.0*
<i>Liquid</i>			
Energy value (MJ kg ⁻¹)	0.0*	12.0	17.9
Carbon content (%)	0.0*	30.0*	46.5
<i>Char</i>			
Energy value (MJ kg ⁻¹)	25.0*	24.7	27.0
Carbon content (%)	72.3	70.0*	78.0*

* = Estimated. See text for sources of other figures

the feedstock is stored in the biochar product. Abatement is greatest for slow pyrolysis, where most carbon is retained in biochar, and least for fast pyrolysis, where char yield is low. The values in Table 5 largely agree with those in Table 3, both in terms of energy product and net CO₂ abatement, with a 20% difference in calculated net carbon abatement for slow pyrolysis with associated energy generation.

“Carbon-Negative” Energy?

It has sometimes been claimed that PBS is a “carbon-negative” energy system, this being an extrapolation from “carbon-neutral” bioenergy systems. Using Eq. 2, and assuming that BM_{tot} is 1 t, BC_{Yield} is 0.4, CO_{2tot} is 0.85 and CSF is 0.75, then the CO_{2fix(100)} is

0.935 tCO₂eq.t⁻¹ (assuming biomass used is then replaced). From Table 4, this is associated with 380 kWh electricity generation, hence, it can be argued that PBS is not only carbon neutral, but in fact a carbon-negative system. This is technically correct but only under the assumption of biomass replacement, namely that the same quantity of carbon in the biomass is taken up as CO₂ through subsequent photosynthesis, and no other land-use emissions are entailed. Furthermore, since PBS is currently an inefficient way of generating electricity, the moniker “carbon-negative energy” can be misleading and generate confusion. If the prime intention is to generate electricity, it is likely far better in most cases to utilize a more efficient conversion technology than pyrolysis.

Biochar, Tool for Climate Change Mitigation and Soil Management. Table 5 Pyrolysis process model results (assumes carbon neutral bioenergy)

Model outputs, carbon stability factor 0.75	Slow pyrolysis	Intermediate pyrolysis	Fast pyrolysis
Energy product (kWh eq kg ⁻¹ oven dry feedstock)	0.38	0.56	1.18
Net CO ₂ abatement (kg CO ₂ eq kg ⁻¹ oven dry feedstock) Pyrolysis	0.96	0.88	0.80
Combustion	0.67	0.63	0.75

Evaluating Carbon Abatement from Biochar

In order to determine the importance of a carbon abatement strategy from PBS (or variants thereof, such as Gasification-Biochar Systems, GBS), a number of questions need to be addressed, taking a systems-wide view, including techniques such as resource assessment, land-use modeling, Life-cycle Assessment and Techno-Economic Modeling.

- How much potential carbon abatement might arise from PBS globally?
- How efficient is carbon abatement through PBS compared to alternative use of the same organic matter across the life-cycle of the system?
- How cost efficient is carbon abatement through PBS in economic terms?

What Is the Potential Carbon Abatement Level?

Carbon abatement from biochar is a function of the amount of biochar produced which, in turn, is a function of the amount of biomass or other organic matter that is available. The resource pyramid approach [65] can be used to distinguish between “theoretical available resources” (i.e., the total amount which exists), “realistic available resources” (which applies a first level of pragmatic judgment to limit the supply), and “viable available resources” (which applies a second level of pragmatic judgment to further limit

supply, taking particular account of likely or possible other demands in the market place). Even so, resource availability scenarios are likely to be necessary to account for irreducible uncertainties in future supply and demand (such as scenarios reflecting lower supply, higher supply, and very high supply of feedstocks available for pyrolysis, or scenarios which reflect low, medium, and high levels of competition for any available biomass for uses other than PBS).

Lehmann et al. [17] estimate that current global *potential* production of biochar is 0.6 ± 0.1 gigatons (Gt) per year (10^9 t or PgC year⁻¹). Lenton [66] argues that the present potential for biochar production from agricultural wastes, forestry fellings, and from shifting agriculture (“slash and char”) is somewhat higher than in [17], increasing the potential carbon abatement through biochar to 0.77–0.87 Gt C (PgC) year⁻¹. Lehmann et al. [17] estimate that by 2100, production of biochar could reach between 5.5 and 9.5 Gt year⁻¹, assuming that biomass is grown specifically for the purpose of PBS. There are very large uncertainties attached to these numbers however, arising from competition for land-use, competition for use of biofuels, agricultural residues, and organic wastes, and a huge divergence (of nearly 1,000%) in different expert estimates of the potential future global supply of biomass for bioenergy purposes (see Box 2). Roberts et al. [56] arrive at a much smaller value for global CA (0.65 Gt CO₂ year⁻¹ or 0.18 Gt C year⁻¹) under the assumption that 50% of the 1.5 billion tons of currently unused crop residues globally is utilized for producing biochar. This might contribute 4% of the carbon reductions that are required globally by 2050 to limit climate change. However, after reviewing the literature on the potential production of biomass for bioenergy by 2100, Lenton [66] arrives at a carbon-abatement value from biochar that compares reasonably well with the larger Lehmann et al. value. He notes the potential constraint in carbon storage capacity in soil arising from biochar addition by about 2100, even assuming a high loading of 140 tC ha⁻¹.

Woolf et al. [68] have created and linked a global biomass feedstock availability model and a pyrolysis biochar production model, and calculate that between 1 and 1.8 Gt C year⁻¹ is feasible by about 2050 from the biochar mitigation option. The range is explained by the use of three different scenarios of biomass supply;

Box 2: Estimates of the Global Potential of Biofuels

A review by the OECD identifies four potential sources of bioenergy: additional land brought into production; crop residues; forest residues; and other organic waste (plant and animal) [70]. The OECD report suggests that, globally, 0.44 Gha is the upper limit on the land area that could be made available for dedicated bioenergy crop production by 2050. Models of land availability tend to underestimate the land that is already in use (by 10–20%), while overestimating the amount of land that could be brought into production. Limited water availability and competition for food and fiber production are frequently overlooked. The OECD estimate on new land available for bioenergy cultivation compares with the average of 0.59 Gha calculated from 11 studies reviewed [71].

The OECD report estimates that the total bioenergy available from the 0.44 Gha of new land is 100 EJ year^{-1} . The potential for marginal and degraded land is put at $29\text{--}39 \text{ EJ year}^{-1}$. As for crop residues, only 25–33% of residues are available for extraction because of competing uses and the need to return some to soil for nutrient replacement. Using yields from IIASA [72], bioenergy from crop residues is estimated at 35 EJ year^{-1} in 2050. The IIASA study estimates bioenergy from forestry residues to be 91 EJ year^{-1} , while other organic residues and wastes are expensive to collect, hence the potential is limited to 10 EJ year^{-1} by 2050 [73]. All in all, the OECD estimates that the primary energy available for heat, electricity, and motive power that could technically be made available globally is 245 EJ year^{-1} , which is at the lower end of the range reported by the IPCC in its Fourth Assessment Report ($125\text{--}760 \text{ EJ year}^{-1}$) [74].

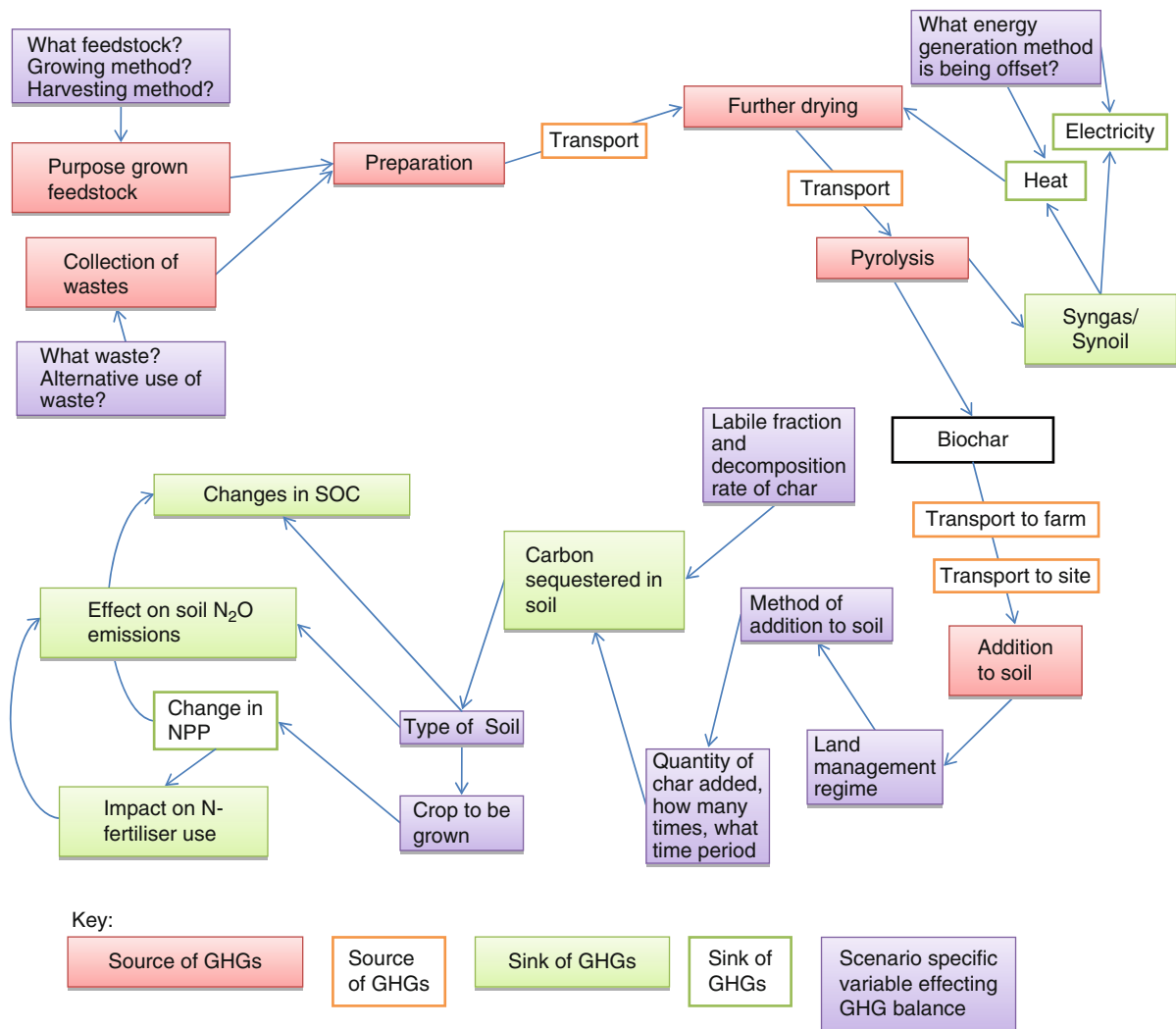
in each scenario, sustainability constraints have been met such that land upon which food is grown is not used for growing biomass for biochar production (i.e., only agri-residues and clean wastes are utilized) and indirect land-use change is not induced, incurring carbon-debt problems. Woolf et al. found that carbon abatement from use of biomass for biochar production was, on average, c. 20% higher than where the same

biomass is used for bioelectricity generation through combustion. The comparison depends however on the fossil fuel offset. Where coal is offset, then biomass combustion and pyrolysis-biochar have similar carbon abatement. The higher bioelectricity generation from use of combustion avoids more carbon emissions due to the high carbon intensity of coal (compared, say, to gas, nuclear, renewables, etc.). Pyrolysis-biochar performs better in terms of carbon mitigation, where offsetting is against a fuel with a lower carbon intensity because the energy penalty of pyrolysis is therefore less important (from a carbon point of view) (a point also made by [69]). A further issue explored by Woolf et al. is the potential role of soil fertility in influencing the carbon mitigation potential of biochar; namely, in areas of low soil fertility, biochar is anticipated to have greater agronomic benefit, increasing yields with the use of fewer inputs (and their associated greenhouse gas emissions). This means that, according to this analysis and in terms of carbon mitigation, biochar is most effective, where it is incorporated into poorer quality soils in regions where less carbon-intensive fuels are being displaced.

The IEA's Energy Technology Perspectives project has suggested that a reduction of $13 \text{ Gt C year}^{-1}$ is needed in 2050 relative to the “do-nothing” business-as-usual scenario [75]. If biochar could contribute 1 Gt C year^{-1} to “filling” this overall $13 \text{ Gt C year}^{-1}$, then its contribution would be roughly similar to the potential role of nuclear power expansion or enhanced power-generation efficiency and fuel switching.

The Carbon Abatement Efficiency of Pyrolysis-Biochar Systems

Carbon abatement efficiency (CAE) is defined as the net carbon abatement delivered for a given function unit (e.g., processing of a unit of feedstock, delivery of a kWh of electricity or heat, utilization of a given area of land, etc.). It is a way of comparing abatement efficiency between alternative uses of the same feedstock, land, or per unit of delivered energy. This is important in deciding how to use limited resources. The CAE is calculated from a life-cycle assessment (LCA) of the full PBS chain. An example of an LCA of a biochar system, including the impacts of biochar in the soil, is illustrated in Fig. 6.



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 6

A life-cycle system model for pyrolysis-biochar systems [55]

A number of LCA studies of PBS have been conducted for a range of different feedstocks, technologies, and agricultural contexts. The results are summarized in Table 6.

Table 6 shows that some studies present significantly higher net carbon-abatement values than others. For instance, Gaunt et al. [59] present values for switchgrass that are several times larger than those of Roberts et al. [56]. Their respective values are closer for corn stover (30% different). At first glance, the net carbon abatement for Miscanthus from Gaunt [59] and Hammond et al. [55] appear to agree, but not

when the results are compared with inclusion of the indirect effects of biochar in soil in the former study (in which case, the Gaunt et al. study has 60–100% greater net carbon abatement than the Hammond et al. study). While some results do appear to converge, the overall impression is of a wide range of different assumptions leading to a high degree of uncertainty. At present, it is not known which assumptions are most appropriate and in what context. For instance, the assumed CSF of studies in Table 6 varied from 0.68 to 1.0 (for a range of [not always specified] timescales). This difference alone can account for a 50% variation in net CA.

Biochar, Tool for Climate Change Mitigation and Soil Management. Table 6 Comparison of different life-cycle assessment studies of pyrolysis-biochar systems

Variable	Description	Gaunt and Lehmann [59]	Gaunt and Cowie [58]	McCarl et al. [76]	Roberts et al. [56]	Hammond et al. (2011) [55]	Ibarrola [57]
Feedstocks		Switchgrass, miscanthus, forage corn, wheat straw, corn straw	Green waste, cattle manure, wheat straw	Maize stover	Corn straw, yard waste, switchgrass	Wheat, barley, and oilseed rape straw, UK and Canadian forestry residues, short-rotation forestry, short-rotation coppice, miscanthus, sawmill residues, arboricultural arisings	Green and garden waste, sewage sludge, food waste, anaerobic digestate, construction and demolition wood waste
National context and applicability		USA	Undefined	USA (mid-West)	USA	UK	UK
Energy ratio	Energy outputs divided by energy inputs	Forage corn: 1.3	Not specified	Not specified	Corn stover: 2.8	Not specified	Not specified
		All others: 4.3 to 5.9			Switchgrass: 3.1		
Overall energy efficiency	Delivered energy (heat or power) divided by energy in feedstock + fossil fuel energy to operate process	38%	Green: 20% Cattle man.: 15% Wheat straw.: 25%		29% Heat	6–15% Electricity	20% Electricity
CO _{2av}	CO ₂ avoided through fossil fuel substitution (% of total)	19–25%	10–18%	Not specified	26–40%	10–25%	20–30%
BC _{yield}	Fresh biochar yield (as proportion of feedstock) (% DM)	8.5–8.7% (fast pyrolysis)	35–42%	35%	29%	33.5%	35%
CSF and time period	Carbon stability factor	1.0 over 10 years	0.75 over 10 years	1.0 time period not defined	0.8 (loss over small number of years then stable)	0.68 over 100 years	0.68 over 100 years

CO ₂ tot	Carbon content of fresh biochar			0.75	0.63–0.68	0.75	C&I wood: 0.72 Green: 0.50 Sewage sludge: 0.38 Food: 0.62
Proportion of the CA that is stabilized C in char (% of total)		58–63%	41–45%	Not specified	54–66%	40–50%	45–55%
Proportion of the CA that is indirect effects of char in soil (% of total)		17–19%	40–48%	Not specified	2–10%	25–40%	15–25%
Assumed size of pyrolysis unit (tons per annum)			16,000	70,000	10 t h ⁻¹ c. 50,000 tpa	Small: 2,000 Medium: 20,000 Large: 100,000	
CO ₂ na (tCO ₂ eq. t ⁻¹ oven dry)	Net carbon-equivalent abatement	Gaunt and Lehmann [59]	Gaunt and Cowie [58]	McCarl et al. [76]	Roberts et al. [56]	Hammond et al. [55]	Ibarrola [57]
	Corn stover			0.8–1.1	0.793–0.864		
	Switchgrass	1.307	1.16/1.82		0.442		
	Green waste/yard waste				0.885		0.855
	Miscanthus	1.328				1.14	
	Wheat straw		0.99/1.65			0.84	
	Cattle manure		1.085/1.745				
	Sawmill residues					1.17	
	Forestry residues					1.24	
	Short-rotation coppice					1.13	
	Sewage sludge						0.774
	Food waste						0.965
	Anaerobic digestate						0.785
	Construction and demolition waste						1.048

Biochar, Tool for Climate Change Mitigation and Soil Management. Table 6 (Continued)

Variable	Description	Gaunt and Lehmann [59]	Gaunt and Cowie [58]	McCarl et al. [76]	Roberts et al. [56]	Hammond et al. (2011) [55]	Ibarrola [57]
Notes		1	2	3	4	5	6
Reference		Gaunt et al. [59]	Gaunt et al. [58]	McCarl et al. [76]	Roberts et al. [56]	Hammond et al. [55]	Ibarrola [57]

1. The CEF assumes 50% coal and gas, hence it is the average of the two values in Table 3 in Gaunt and Lehmann [59] converted from per hectare to per ton basis using the yield figures provided in the paper. The yield for corn stover is not given, so the CO₂na cannot be calculated.
2. The CEF assumes 50% coal and gas, hence it is the average of the two values in Table 18.2a ([58]). The first value shown does not include the application of biochar to crops or indirect effects of biochar upon soil incorporation. The value of these effects can be inferred to be from 0.2 (low), 0.66 (medium) and 1.14 (high) tCO₂eq.t⁻¹. The second value shown uses the medium values of the indirect effects and adds this quantity to the pyrolysis + fossil fuel offsets value. If the lower estimate of the indirect effects is used instead, the overall effect is reduced by c. 0.4 tCO₂eq.t⁻¹. In calculating the proportional contribution to total CA from the avoided fossil fuel emissions, stabilized carbon in char and the indirect impacts of biochar in soils, the medium value of the indirect effects have been assumed.
3. Lower value for switchgrass refers to slow pyrolysis; the higher value refers to fast pyrolysis.
4. For corn stover, the lower value is early stover and the higher value is late stover. In the case of the switchgrass, this does not take account of indirect land-use change (ILUC) arising from use of bioenergy crops. If ILUC is included, then the net carbon abatement is -0.036 tCO₂eq.t⁻¹ (i.e., an emission).
5. The value for wheat straw is the same as for barley and oilseed rape straw. Where large quantities of forestry residues are imported into the UK from Canada, the CO₂na is 1.08 tCO₂eq.t⁻¹. The value for short rotation coppice (SRC) is similar to the values for small round wood (1.15 tCO₂eq.t⁻¹).
6. Results for green waste, sewage sludge, and food waste are relative to incorporation of material in landfill sites with UK-levels of methane recovery. Values are also provided for incorporation of material into fast pyrolysis (10% char yield).

Different assumptions about useable or delivered energy from pyrolysis are also important contributors to the uncertainty. Some studies assume a much higher energy conversion efficiency than others, e.g., Gaunt and Lehmann assume a value that is substantially higher than conventional biomass combustion, and even gasification, suggesting that useable heat is also being utilized. Roberts et al. also assume effective use of heat from pyrolysis, hence use a high overall energy efficiency. Hammond, on the other hand, uses a more conservative value for net energy efficiency, which is substantially lower than straight combustion. How energy is treated in the LCA is important in making comparisons with CA from straight combustion or gasification since it is frequently assumed that heat is not readily used from such technologies where the principal purpose is electricity generation. Comparing net CA from PBS with delivered power and heat with biomass combustion with only power generation is probably not a fair comparison to make.

Some element of “biochar proponent optimism” has likely entered into the existing studies, and a more critical approach will be needed for the future. In summary, there is a moderate to high level of uncertainty attached to all existing values, and one should not pay too much attention to the precise numbers as they are very likely to change in the future as more understanding and experience is gained. The lack of reliable engineering data on the slow pyrolysis process at a commercial scale is one of the critical uncertainties. Most of the existing studies have used data from a single technology (BEST Energies, now Pacific Pyrolysis Pty. Ltd.), yet the results from this process have not been published in the peer-reviewed literature. This creates a potential weakness in the current argument in favor of biochar that needs to be addressed by acquisition of much better engineering data on slow pyrolysis.

Energy-Output to Energy-Input Ratios

The energy-output to -input ratio (also known as the energy yield) is the quantity of delivered energy (i.e., useable power and/or heat) divided by the quantity of energy required to produce that energy. Bioenergy systems typically utilize as fuels widely distributed biomass resources which require energy – frequently supplied by energy dense fossil fuels – to cut, prepare,

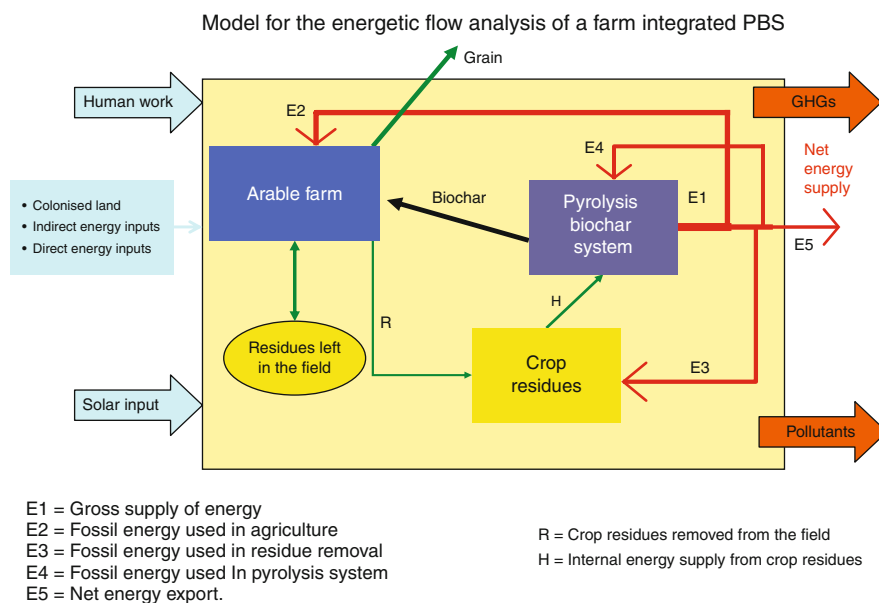
transport, store, process, and ignite feedstocks. Fossil fuel-derived energy is also required to manufacture, transport, and erect the equipment and infrastructure that is needed for the bioenergy system to function. In calculating the energy ratio, the energy content of the biomass itself is not included as an energy input since this is treated as “free energy,” having been derived from the sun’s energy through plant photosynthesis. The biochar energy system can be depicted as a set of inputs and outputs as in Fig. 7.

The energy ration in Fig. 7 is calculated as:

$$\text{Energy ratio} = \frac{\text{net energy output}}{\text{energy inputs}} = \frac{E5}{E2 + E3 + E4}$$

The use of highly dense energy sources (fossil fuels) to enable the utilization of very distributed bioenergy sources has to be carefully assessed to avoid the problems that have beset the production of bioethanol from maize in the USA. In that case, the energy output/energy input ratio (at between 0.7 and 2.2 MJ MJ⁻¹) is generally too low for the system as a whole to make energetic sense: what happens in effect is that the energy content of fossil fuels is being released to produce bioethanol with a similar energy content. The energy output/energy input ratio needs to be 2.0 or more for a bio-energy system to make energetic sense [77].

Several estimates of the energy-output/energy-input ratio of PBS are available, though due to the lack of reliable data on the pyrolysis process itself, especially at commercial scale, such estimates remain tentative. Gaunt et al. [59] provided a range of values that range from 2.3 to 7, depending upon the feedstock. However, Gaunt et al. use the gross energy output in calculating the energy yield, whereas the convention is to utilize the net energy output. The recalculated energy yield ranges in [59] from 1.3 (forage corn), 4.3 (switchgrass), 4.6 (miscanthus), to 5.9 (wheat straw and corn stover). The highest energy yields are associated with the use of crop residues (wheat straw and corn stover) since the energy inputs are lower for these feedstocks than for dedicated bioenergy crops (switchgrass and miscanthus). The study [59] assumes a biochar yield of c. 8.5–9%, with 38% of feedstock energy available as delivered energy. If a more modest net energy efficiency of 15% is assumed, however, then the energy yield is reduced to 1.1 (switchgrass), 1.2 (miscanthus), 0.1 (forage corn),



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 7

Pyrolysis-Biochar as an Energetic System (Jason Cook after Giampietro and Mayumi [77])

and 1.7 (wheat straw and corn stover). With a more conservative, and some would argue, more realistic assessment of the net energy efficiency, the energy yield falls below the critical value of 2 and is unlikely to make energetic sense.

Roberts et al. [56] provide values for the energy ratios of 2.8 for corn stover and 3.1 for switchgrass; however, as with Gaunt et al., this study makes highly optimistic assumptions regarding the net energy efficiency, using a value of 37%, requiring productive use of the heat from syngas combustion. Reliable and economic markets for heat from power plants are notoriously difficult to create, and much analysis avoids inclusion of heat in calculations of avoided fossil fuel emissions for this reason. It is therefore optimistic to assume effective markets for heat from pyrolysis plants, therefore. If the more conservative assumption is made that only electricity generation from pyrolysis at 15% efficiency will find an economically viable market, then the energy yields from Roberts et al. can be recalculated downward as follows: late stover from 5.5 to 1.65, early stover from 3 to 0.63, switchgrass from 5.5 to 1.65, and yard waste from 9.5 to 2.4. The energy yields turn out to be highly sensitive to the efficiency of the conversion process to delivered energy.

Assuming that Giampietro and Mayumi are correct in identifying 2 as a critical value for the energy yield for biofuels, below which the basic energetics of bioenergy systems cease to make sense, then it is apparent that pyrolysis-biochar systems need to be operating at net energy efficiencies of at least 20–30%, depending upon the individual feedstock and technology assumptions. Anything which increases the use of fossil fuels in the PBS (*ceteris paribus*) will also pose a challenge to the system energetics. Roberts et al. [56] report, for example, that an increase in transportation distance from the baseline (15 km) to 200 km reduces the net energy by 15%, while at 1,000 km, the net energy decreases by 79%. An 80% reduction implies an energy yield of 1 or below, but even a 15% reduction in net energy could bring the energy yield below 2.

More work on accurate calculation of energy yields is therefore urgently required. The most promising scenarios will be where forestry residues and other organic wastes are being utilized, i.e., where fossil fuel inputs to the provision of the feedstock are minimized (in the case of many wastes because some form of treatment is required in any case) and where long transportation distances are not required. The carbon-equivalent production emission for sawmill

residues in the UK is $4 \text{ kgCO}_2\text{odt}^{-1}$, while in the case of forestry residues, there is a negative emission of c. $50 \text{ kgCO}_2\text{odt}^{-1}$ as a consequence of avoided methane emissions from wood that otherwise decomposes [55]. UK arable straw entails a higher production emission of c. $200 \text{ kgCO}_2\text{odt}^{-1}$ (partly because c. 15% of the fossil fuels required for the arable crop production are allocated to the straw on economic grounds) [55]. This is actually greater than the production emissions of SRC and Miscanthus in UK conditions, where chemical fertilizers are not used (c. $20\text{--}40 \text{ kgCO}_2\text{odt}^{-1}$). Utilization of sewage sludge in SRC and Miscanthus results in higher N_2O emissions, though the sludge has to be disposed of in the baseline case so could arguably be ignored in LCA calculations.

It could be argued that if a key purpose of PBS is carbon abatement, critical values arising from energetic analysis are not necessarily relevant. This point may be valid, where the production of energy from the biomass is an ancillary benefit of a PBS development. For instance, the main purpose of a project may be the more effective disposal of an organic waste stream, and energy production a fortunate by-product and bonus: the waste would otherwise need to have been managed in some fashion. Yet, where the biomass has an alternative use as a fuel in co-firing, anaerobic digestion (AD), fermentation, dedicated biomass combustion or gasification, and where a market for such biomass and for bioenergy exists (e.g., whether with or without the aid of incentives), then an energetic analysis is appropriate to use. This is because a lower energy yield has to be compensated by increased energy production (or reduced demand) from some other part of the system.

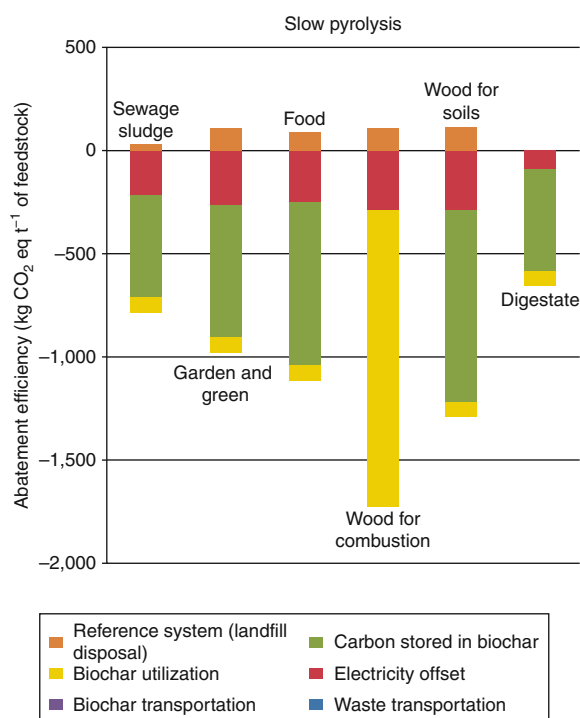
Key Findings from Existing LCA Studies

Feedstock Suitability Hammond et al. [55] found that systems which utilize woody residue feedstocks tend to have the highest CAE, closely followed by purpose-grown woody feedstocks. Small-scale straw-based systems have a 15–30% lower CAE than wood residues, partly because of assumed scale-factors; the rest of the difference is explained by higher inputs for straw-based systems versus wood residues.

Roberts et al. [56] examined the impact of land-use change arising from the conversion of cropland from

annual crops to perennial switchgrass (direct change) and the subsequent need to convert land to cropland to replace lost agricultural land (indirect change). They included two estimates of the size of these direct and indirect land-use changes (886 and $406.8 \text{ kgCO}_2 \text{ t}^{-1}$ dry switchgrass). If the larger land emission value is used, then the overall CA of the PBS is negative (i.e., a positive emission of $36 \text{ kgCO}_2 \text{ t}^{-1}$), but is positive if the lower land-use-change value is used ($442 \text{ kgCO}_2 \text{ t}^{-1}$). Roberts et al. comment that PBS could conceivably *increase* net radiative forcing from GHG emissions if direct and indirect land-use-change emissions are associated with energy-crop establishment.

Ibarrola [57] found that biochar production from pyrolysis of wood waste (construction and demolition, plus commercial and industrial), garden and green waste, and food waste have greater CAE than sewage sludge or AD digestate (Fig. 8). This is because of the higher calorific value of the former, and the higher stabilized carbon content of their biochar product. Gaunt and Cowie [58] present a similar figure for CA



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 8

CA of PBS using different nonvirgin biomass feedstocks

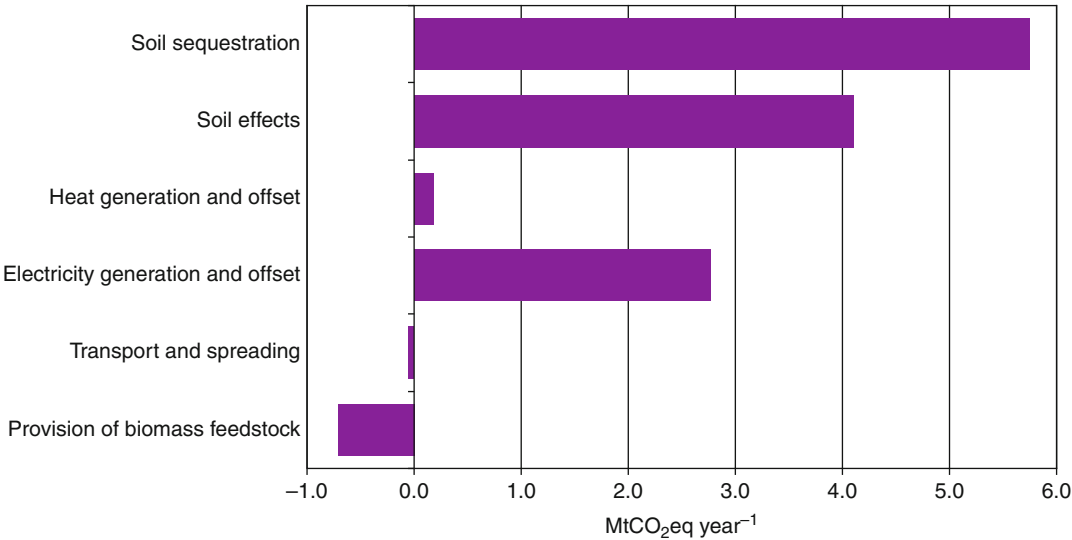
of green waste compared to conventional landfill with CH₄ recovery (1.0–1.2 t CO₂eq.t⁻¹ oven dry feedstock). Joseph et al. [79] have recently presented more results for a range of nonvirgin biomass feedstocks in Australia, including poultry litter, paper sludge and green waste: the CA is between 1.4 and just over 2.0 t CO₂eq.t⁻¹ oven dry feedstock, the somewhat higher values being explained by the assumed waste-management baseline (which recovers less CH₄ emissions than is typical for many European countries).

Life-Cycle Stage Contributions to Carbon Abatement

Hammond et al. found that the largest contribution to CA is from stabilized carbon in biochar, accounting for approximately 40–50% of total CA. The next largest contribution is from the indirect impacts of biochar in the soil, all of which are currently uncertain: lower crop fertilizer requirement, lower soil N₂O emissions and increased SOC. These account for 25–40% of CA (the proportion changing with the size of other CA categories). The third major CA category in Hammond’s et al. study is fossil fuel offsets from renewable electricity generation at 10–25% of total CA. Similar information is presented in Fig. 9 in which the life-cycle stages of the UK lower resource supply scenario are broken-down to illustrate CO₂ emitting and abating stages.

In the Roberts et al. study, the proportion from stabilized carbon in the biochar is larger at 54–66%. The proportion from avoided fossil fuel emissions is also larger at between 26% and 40% depending on feedstock.

The main difference between Hammond et al. and Roberts et al. is that the former study assumes a higher value for the indirect soil impacts of biochar, principally due to the assumed accumulation of soil organic carbon as a consequence of biochar addition. As a consequence, the proportional contribution of stabilized carbon and avoided fossil fuel emissions is lower than in Roberts et al., which makes more conservative assumptions about the indirect impacts of biochar in soil. Of the studies reported in Table 6, the indirect impacts of biochar in soils upon net carbon abatement tend to be smaller than assumed in Hammond et al., although Gaunt and Downie assume even higher values. Ibarrola’s study presents a similar contribution breakdown as Roberts: the largest contribution to CA for both fast and slow pyrolysis in the case of wood, food, and green wastes is carbon stabilized in biochar (45–55%, excluding use of digestate case). The second largest contribution comes from offset GHG emissions from fossil fuel emissions (20–30%). Where the assumed indirect impacts are lower, then the contribution of stabilized carbon and avoided fossil fuel emissions are



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 9
CO₂eq abatement by life-cycle stage for lower biomass supply scenario (UK conditions)

proportionally higher. The studies in Table 6 indicate that transport emissions are a relatively minor contribution to overall lifecycle emissions (several percent for biomass and biochar movement of c. 20 km each).

CO₂ Equivalent Emissions Per Unit Delivered Energy

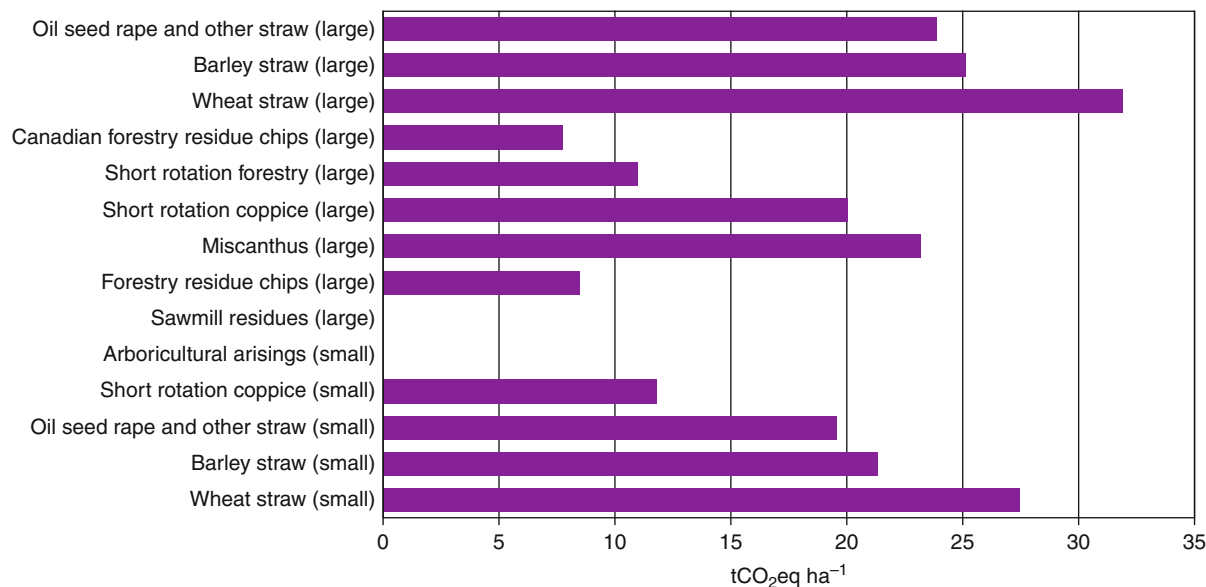
Hammond et al. presents a carbon abatement for PBS of 1,500–2,000 kg CO₂eq MWh⁻¹ (1.5–2.0 kg kWh⁻¹) for large systems, compared to a UK CEF of 0.56 kgCO₂kWh⁻¹ in 2006 [53]. For comparison, modern bioenergy systems (combustion with grate or fluidized bed, gasification) produce emissions from between 0.03 and 0.07 kg CO₂ kWh⁻¹ [80], or from 0.05 to 0.30 kg CO₂ kWh⁻¹ according to the Environment Agency [81]. While PBS appears to offer far better CA MWh⁻¹ than conventional bioelectricity, this is a somewhat misleading finding. Much of the CA from PBS results from stabilized carbon in the biochar and from indirect soil effects (rather than from offset fossil fuel emissions), while the denominator – electricity generation per unit biomass – is lower than for conventional bioelectricity due to lower efficiency. Thus, the CA per unit electricity is high, but electrical efficiency is low.

CO₂ Equivalent Emissions Per Hectare

On an area basis in the UK, Hammond et al. found that CA ranges from seven to nearly 30 tCO₂eq ha⁻¹ year⁻¹, depending on PBS feedstock (Fig. 9). Waste feedstocks such as arboricultural arisings are the most efficient in terms of land use as they do not require any additional land use change and do not interfere with crop-production systems; moreover, they are commonly disposed of as wastes and hence PBS incurs less emissions through additional transport, handling, and storage stages. Such numbers compare favorably with conventional bioenergy in the UK, which abate between 1 and 7 tCO₂eq ha⁻¹ year⁻¹; the most productive biofuel system in the world – bioethanol from sugar cane in Brazil – abates c. 16 tCO₂eq ha⁻¹ year⁻¹, so biochar performs well under this metric (Fig. 10).

Delivered Energy Generation from Pyrolysis-Biochar Systems Versus Combustion

Roberts et al. compared use of biochar for soil with use of biochar to replace coal and found that biochar to soil resulted in 29% more carbon



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 10

Annual CO₂eq abatement per hectare for UK conditions. No value is given for sawmill residues or arboricultural arisings since the plants are not grown specifically for pyrolyzable residues

abatement (627 vs 864 kgCO₂eq t⁻¹). A more realistic comparison is between PBS and direct biomass combustion and, in this case, Roberts et al. found that carbon abatement was actually less for PBS than for combustion (987 vs 864 kgCO₂eq t⁻¹) (using a CEF for natural gas). On the other hand, approximately half of the CA from PBS involves removal of CO₂ from atmosphere, compared to biomass combustion, where all the carbon abatement arises from avoided fossil fuel emissions.

In Hammond's et al. study, PBS performs somewhat better compared to combustion than in Roberts et al., partly reflecting somewhat higher CA per ton feedstock in the former than in the latter. The comparison depends upon the relative energy efficiencies of the two processes and upon the CEF used to calculate avoided fossil fuel emissions. For example, at an efficiency of 15% and with a CSF of 0.68, PBS appear to offer greater CA than combustion at 33% efficiency (using an average UK grid CEF) even without inclusion of indirect soil effects, but cannot compete with combustion (or gasification) at an efficiency over 40%. In systems co-firing biomass with coal, efficiency can be significantly higher in new plants (up to 42%). Hence, either the indirect benefits of biochar upon net GHG emission fluxes would need to be on the scale proposed in Hammond or else the efficiency of the PBS would need to increase (or some combination of the two). Where biomass co-firing is combined with CO₂ capture and geological storage (Bioenergy CCS, or BECCs), PBS is not able to compete in terms of carbon abatement (because the CCS process captures c. 90% of the carbon in the feedstock compared to c. 50% of feedstock carbon conserved during pyrolysis).

If grid average of 80 kg CO₂eq MWh⁻¹ is attained by 2030 (which is required in the UK context if the government's carbon-reduction targets of an 80% reduction by 2050 relative to 1990 levels are to be met) and assuming biomass is still available as a resource, biomass combustion offers almost no carbon abatement benefit [82]. PBS meanwhile still offers CA benefits, i.e., it has net negative CO₂eq MWh⁻¹ emissions. Yet, as noted above, at current net energy efficiencies, PBS is unlikely to be the technology of choice for generating electricity so it may have a rather limited role.

From the results of Roberts et al. and Hammond et al., it is evident that PBS is not necessarily more efficient in terms of CA than other bioenergy options: it will depend on the detailed analysis of each individual case. It is clear in general that conversion of the energy in feedstock into useful delivered energy (heat and power) will have to be reasonably efficient (20–30%) for PBS to compete on any scale with direct combustion. In the longer-term perspective, however, PBS may become more valuable (compared to combustion technology) due to its ability to actually remove carbon from the atmosphere. Exactly when this benefit would be realized is highly uncertain and context-dependent (e.g., reliant upon the outcome of other highly uncertain processes).

Sensitivity Analysis

Hammond et al. found that the following variables were all important in influencing the overall net carbon abatement: total handling losses, char yield, total electrical efficiency, use of heat, soil organic carbon accumulation, the allocation of GHG emissions to the production of the feedstock, fraction of labile carbon and – most importantly – the Mean Residence Time (MRT). If the MRT is below 500 years, there is a reduction in the CAE which begins to look concerning, although this partly depends on the time horizon over which an analysis is undertaken. Hammond found low sensitivity to the following variables: distance travelled (biomass and biochar) (up to 200 km), reduced nitrogen fertilizer application (0–50%), and reduced nitrous oxide emissions (0–100%).

In their LCA, Roberts et al. identified broadly similar sensitivities to Hammond et al. The results were sensitive to: emissions entailed in feedstock collection, stability of the carbon, biochar yield, and syngas yield. There was a lack of sensitivity to N₂O emission suppression and to distance travelled (except where this was 500 km +). Needless to say, the results of any such LCA are sensitive to the assumed CEF of the fossil fuel which is offset.

There are large uncertainties associated with the LCA work presented here. Biomass production systems vary in space and with time, making a calculation using a single number problematic. For the nonvirgin waste feedstocks, considerable uncertainties occur with

respect to the management of individual landfill sites (e.g., the biodegradable fraction, oxidation factors, CH₄ recovery, etc.), making comparison of PBS to existing options difficult.

How Cost-Effective Are Pyrolysis-Biochar Systems?

Gaunt and Lehmann [59] calculated that the cost of reducing a ton of CO₂ in the PBS they examined was between \$9 and \$16 compared to utilizing the same char as a fuel. Since they did not undertake a full economic costing, this figure does not allow comparison with other marginal abatement carbon costs (MACCs).

McCarl et al. [76] undertook a full economic costing and found that the net present value of the PBS examined (70 ktpa corn stover, mid-west USA conditions) was $-\$70 \text{ t}^{-1}$ feedstock for slow pyrolysis and $-\$45 \text{ t}^{-1}$ for fast pyrolysis, i.e., it is a loss-making venture under these assumptions. This assumed a carbon value of $\$4 \text{ tCO}_2^{-1}$ abatement and an agronomic value of $\$33 \text{ t}^{-1}$ biochar or $\$11.5 \text{ t}^{-1}$ feedstock. The biochar production cost (i.e., ignoring revenues from biochar as a form of carbon storage or arising from its agronomic value) is therefore approximately $\$85 \text{ t}^{-1}$ feedstock or c. $\$240 \text{ t}^{-1}$ biochar. The “energy penalty” cost of utilizing char as a soil amendment rather than as a fuel is $\$40 \text{ tCO}_2^{-1}$, considerably higher than Gaunt and Lehmann’s estimate of $\$15 \text{ tCO}_2^{-1}$, though similar to other estimates (e.g., Lehmann [9]).

Roberts et al. [56] present data on net present value of their USA-based PBS (c. 50 ktpa) which appears to indicate some positive NPVs. This is as a consequence of a very high carbon-price assumption ($\$80 \text{ tCO}_2^{-1}$). Even their “low” carbon price ($\$20 \text{ tCO}_2^{-1}$) is actually higher than the 2008–2010 EU ETS market value of $\$10\text{--}20 \text{ tCO}_2^{-1}$. If we remove the carbon revenue from the calculation along with the small benefit in increased fertilizer efficiency (but retaining the value of the P and K nutrients in the char), the NPVs are all negative. The production costs, expressed per ton of biochar, are: $\$155 \text{ t}^{-1}$ for late stover, $\$124\text{--}142 \text{ t}^{-1}$ for switchgrass, and $\$13 \text{ t}^{-1}$ for yard waste. These costs are lower than McCarl et al. [76], but not much so (40% or so lower). The exception is for yard waste in which case the cost of production is much lower due to the revenue gained through tipping fees and the other avoided costs of organic waste management.

Shackley et al. [158] present economic data on the situation in the UK for a range of feedstocks, with three plant sizes (small: 2 ktpa; medium: 16 ktpa; large: 184 ktpa). They provide a range of values of the costs of biochar production from $-\$220$ to $\$580 \text{ t}^{-1}$. The negative values arise from waste feedstocks, where there is a revenue stream from tipping fees which can otherwise be large in the UK context. The production costs are typically lower for the large-scale pyrolysis units due to lower capital, operational, and maintenance costs per unit production. The costs also vary depending upon the assumed storage option. For the virgin feedstocks, production costs are closer to McCarl et al. than to the Roberts et al. estimate above.

Brown et al. [161] compared the internal rate of return (IRR) for slow and fast pyrolysis assuming an increasing carbon price to 2030, use of gas co-product for heating and bio-oil refined to gasoline (in the case of fast pyrolysis only). The projected IRR for slow pyrolysis is negative out to 2030 for feedstock costing $\$83$ per ton. A zero cost feedstock would deliver an IRR of between 8% and 17%, but this is not considered sufficiently profitable for investment in a new technology. Brown et al. [161] found that the profitability of both slow and fast pyrolysis depended primarily upon the value of the energy product(s). Yoder et al. [162] develop a product transformation curve using optimisation and econometric analysis of existing data for quantifying the trade-off in pyrolysis between bio-oil and biochar production.

As for the LCA, costs are typically context-specific, and there are some niche applications where the NPV will be more evidently favorable, e.g., where a type of biochar has a high agronomic or soil-related value. A further example is where the biochar is a “waste” product from an economically viable energy project (Box 3).

To summarize, the economic viability of biochar production and application are currently highly uncertain. Feedstocks – especially clean ones – are frequently expensive in developed countries and increasingly in demand by other users such as for Anaerobic Digestion, composting, combustion, gasification, and so on. Technology costs associated with pyrolysis are especially hard to predict at the present time, and most estimates in the literature are based upon one or a few designs. At present, the incentives structure in most

Box 3: Gasification of Rice Husks: Case Study from Cambodia

Rice husks are gasified in an Ankur gasifier to produce syngas that is fed into an engine that powers a rice mill. The system is economically viable (due to mill being off-grid, hence otherwise having to rely upon expensive diesel fuel for power generation). Carbonized rice husks (CRHs) are the waste product, which accumulate, and can become an environmental problem. The CRH yield is c. 30%, and the carbon content of the char is c. 35%. Therefore, for each ton of rice husk, 300 kg of CRHs are produced containing 105 kgC or 385 kgCO₂. The labile C content is <1% and the CSF is 0.92 hence the stabilized carbon content is c. 350 kgCO₂t⁻¹ biochar. The cost of application to agricultural fields in Cambodia is low – estimated at \$1t⁻¹, while the agronomic value (based upon unpublished research) appears to be c. \$2 to 8 t⁻¹. Since the CRHs are (currently) free, the value of the biochar is c. \$1 to 7 t⁻¹; this is an important potential source of additional income in a subsistence farming system such as Cambodia.

If the rice husks were otherwise disposed of in irrigated paddy, there is also the value of avoided methane emissions from gasification. For every 1 t of applied rice husks, 40 kg of carbon is converted into 53 kg of methane, equivalent to 1,219 kg CO₂.

If the stabilized carbon can have a value, say at \$5 t⁻¹ CO₂, then the additional value of the CRHs is \$1.6 t⁻¹ biochar. Adding to the agronomic value, the overall value is between \$3 and 8 t⁻¹ biochar. And if the CA value of the avoided CH₄ emission is included, this would further rise to about \$9–14 t⁻¹ biochar. Clearly, if the CRHs do indeed have a demonstrable and predictable agronomic value, demand for its use may increase, and the producer may begin to sell the CRHs rather than give it away free as a waste product.

countries is focused upon renewable electricity generation, and there is no mechanism for rewarding stabilized carbon abatement in the soil. If carbon abatement is the primary policy driver, inclusion of stabilized carbon in biochar and its indirect impacts on soil GHG fluxes would need to be given some value alongside renewable electricity generation. One problem with carbon-based land crediting is that it raises the

issue of how to establish a baseline, and many current land-owners and occupiers, e.g., farmers, are reluctant to begin to establish inventories of carbon-equivalent fluxes over their land (such as might be required to establish a baseline against which a biochar project could be assessed). Some countries, e.g., in Europe, have previously expressed their skepticism at including land-based carbon crediting as a major carbon-abatement strategy within the UNFCCC. Scientific uncertainties and technical challenges surrounding monitoring, verification, accounting, and reporting (MVAR) in relation to biochar additions will mean that developing a robust methodology for inclusion of biochar in carbon markets (voluntary or through the Clean Development Mechanism) will be challenging until scientific knowledge improves.

Where biochar is potentially more economically viable is where it is able to treat wastes that incur high tipping fees to landfills. In those situations, PBS may be a cheaper disposal route than landfill or incineration. Whether the char produced can be used in agricultural soils remains uncertain due to the risk of contamination. At present, there is a lack of a clear risk assessment and regulation pathway for such substances. A further situation where biochar might already be economically viable is the case of gasification char – which is a waste product of a financially solvent energy generation technology. If this char can be shown to be beneficial to soils and to avoid introducing contamination, then it could be financially viable to distribute such material to agricultural systems.

What Are the Impacts of Biochar on Soil?

In this section, we turn to the question of the impacts of biochar on soil. A summary of the published literature has been presented previously [6, 7]. Much of the evidence comes from the study of charcoal in the natural environment: this provides the only source of relevant direct evidence for long-term stability of biochar, having been used historically by humans or as a result of deposition after periodic fires in many natural ecosystems. Given the similar formation and chemical characteristics, charcoal in the natural environment provides a powerful tool to investigate the long-term stability of biochar. However, the short-term impacts of biochar may not be well represented in studies of old charcoal.

This is in part because the feedstock can be quite different, and partly because the more complex composition of biochar is overlooked. Also, any labile components associated with the charcoal will have been mineralized prior to sampling.

The more temporary beneficial impacts of biochar may be chemical and result from leachable ash and modification of soil pH, promotion of short-term microbial activity, including the effect of small labile fractions. Physical benefits may arise from modification of soil bulk density, water holding capacity, and promotion of soil aggregation (possibly in combination with soil biological effects). These effects may be temporary or long term. Thermal properties may change as well [83].

Other effects relate to the provision of cation exchange capacity (CEC) and specific surface area (SSA), biological associations (with micro-organisms, fungi, and with plant roots), and bio-physical benefits (mediating the connection of micro-organisms and microbial substrate, promotion of mesofaunal activity, including earthworms). The potential for detrimental effects on the soil would depend on the source of the biochar applied, and the rate and timing of its application. Negative impacts could include leaching of nutrients, addition of toxic elements (metals), or the introduction of organic contaminants. Where biochar has a high affinity for nitrogen, there may be negative short-term effects on crop nutrient supply, i.e., potentially reducing nitrogen availability to the plant in the period after application [84].

Scientific research of biochar is a relatively new topic, and therefore generality in site-specific observations is not yet apparent, while extrapolation from individual observations is not yet possible. At this point, a convergence in methodologies has not emerged and until recently, there have been no strategic research programs to provide a systematic evaluation. The nature of PBS also demands coordination and consolidation of research efforts with pyrolysis engineering in order to produce selected biochar that expresses particular and possibly multiple beneficial functions in soil.

Key Functions of Biochar

Provision of Labile Organic Carbon Rapid utilization of labile substrates in soil can build a store of

nutrients in soil microbial biomass, which may become available for plant acquisition and growth over time. The potential benefits of labile carbon in soil can create a constraint to crop growth if substrate nitrogen is low, and if at the time of addition inorganic (i.e., available) nitrogen in the wider soil is limited. This is because nitrogen as well as carbon is required to build new biomass, and microbes will out-compete roots.

Nitrogen is progressively volatilized during pyrolysis so the ratio of carbon to nitrogen in biochar is generally much higher than in the feedstock. However, if biochar is entirely stable, it will not present the readily accessible carbon substrate necessary to create microbial demand for external nitrogen. Whether significant nitrogen immobilization of soil nitrogen occurs should therefore depend on the size of the biochar addition, the size of the labile fraction, and whether the ratio of nitrogen to carbon of the labile fraction reflects that of the bulk biochar sample.

Storage of Stable Carbon The stable portion of biochar is the fraction for which, in the future, a carbon credit might be claimed and, for the purpose of climate-change mitigation, may be the component that remains in the soil for at least 100 years [7]. There is, as yet, no robust methodology for establishing the MRT of a specific biochar product: this is one of the key scientific uncertainties and policy needs. The sum of stable and labile carbon should not reflect the total carbon content of biochar as fractions of intermediate stability are also likely to be present.

Supply of Plant Available Nutrients Aside from nitrogen, most potential nutrients in pyrolysis feedstock are largely conserved during pyrolysis (as also are potentially toxic elements). Progressive elimination of carbon, oxygen, and hydrogen during pyrolysis therefore increases the total concentration of minerals in the char residue, and in potentially extractable forms as ash. Biochar ash content increases in inverse proportion to retained carbon feedstock, analogous to that which arises during combustion but distributed within a complex physical matrix.

Solubilization of ash may result in minerals becoming available to plants on addition to soil, although since phosphorus (as phosphate) is rapidly complexed with minerals in soil, this may depend on scavenging

directly from char by roots or symbiotic mycorrhizal fungi. In general, introduction of readily available crop nutrients can promote mineralization of organic matter, especially in marginal environments.

However, porosity, and more specifically pore connectivity, may control the release of soluble nutrients from char, making release progressive rather than instantaneous as may be the case in the solubilization of combustion ash. This process could be associated with the mineralization of condensed tars and oils that appear to block biochar pores [85].

Modification of Soil pH The typically alkaline nature of biochar may increase microbial activity in acidic soils by increasing pH and with this, another potential source of “priming” for the decomposition of pre-existing organic matter, although modification of soil pH may also increase plant productivity and thus the amount of carbon substrate added to the soil through roots and residues. Mass for mass, the value of char in pH modification may be up to one third that of agricultural lime [86] and at experimental rates can increase soil pH by 1 unit.

Modification of Soil Physical Characteristics

Depending on the distribution of particle size in the soil, the rate and nature of biochar applied and the time since application, soil pore-size distribution and water holding capacity may be affected. Porosity in char may occur at a range of scales, which affects the proportion of water that can be retained, and equally the accessibility of held water and solutes to plants which can exert sufficient tension to extract the contents of macropores (0.1–30 μm diam) that may not drain naturally. Structurally sound pores of this dimension are abundant in fresh wood-derived charcoal [87], and the connectivity of the relatively small number of larger pores has been investigated in three dimensions by tomography [88].

However, the fresh particle size of powdery charcoal created from grass feedstocks appears to be less than 50 μm [89], and weathered charcoal, while generally found in larger fragments, also resides in this size range [90]. In clayey soils, particles may be less than 5 μm [91]. During weathering, and particularly for char from woody substrate, the position of char fragments within the soil mineral matrix is likely to alter over time. The

effect that this has on total porosity, accessible pores, and accessible surface areas has not been explicitly examined.

Nonetheless, while initially macroporous, it is established that the great majority of total porosity in wood-derived charcoal may reside in micropores of nanometer size [92]. Oils and tars could represent less stable components of biochar around which microbial activity could promote micro-aggregation, relevant to water infiltration and resistance to water erosion. An apparent role for charcoal in aggregation has been observed in field soils [90], although short-term incubation with activated charcoal did not cause aggregation under controlled conditions [93].

Cation Exchange Capacity and Sorption Progressive abiotic and biotic surface oxidation of charcoal results in surface proliferation of carboxyl groups and an increasing ability to sorb cations [33, 34], explaining high cation exchange in archaeological soils [35]. Negative charge provides the possibility for reversible storage of available nitrogen (ammonium, NH_4^+) relevant to soil-based N_2O emissions and nitrate leaching. A mechanism based on the dehydration of phosphate and charcoal has also been described for the adsorption of phosphorus [94], which may explain the apparent impact of biochar on crop phosphorus uptake, possibly aided by arbuscular mycorrhizal fungi [95].

Charcoal has the capacity to sorb polar compounds, including many environmental contaminants [96], particularly PAHs for which it may be the dominant sink in soils and sediments [97]. The significance of biochar addition in removing contaminants from the environment depends on its capacity to fulfill this function relative to charcoal, the affinity (security and reversibility) of stabilization, and the ultimate fate of both char and contaminants [164].

Microbial Activity The possibility that biochar catalyses breakdown of organic matter by providing microbial habitat alone is improbable since sustainable microbial proliferation depends on a renewable source of accessible carbon substrate as well as nutrients. Provided that the majority of biochar carbon is highly stable, after an initial flush of mineralization, microbes that inhabit biochar pores will depend primarily on the indirect effects of biochar to obtain an enhanced supply

of substrate. This could either be through the capture and retention of soluble organic matter otherwise lost to deeper horizons or watercourses, or through a change in loci of plant root activity. Increased plant productivity however should be reflected in increased exudation of carbon through roots, and the deposition of carbon from residues of above-ground growth. The complication that this adds to interpretation of field data has been highlighted by Major et al. [98].

Many plants can form symbiotic associations with mycorrhizal fungi, whose filamentous hyphae provide an extension to plant roots which can enhance acquisition of both nutrients and water, at the expense of some host plant carbon. Although potentially limited by inoculum, soil-chemical conditions and the abundance of exploitable nutrients are more likely to limit mycorrhizal proliferation in most circumstances. Reported promotion of mycorrhizal activity by biochar [99, 100] could reflect utilization of reversible stores of water and soluble nutrients, or exhaustible “mining” of nutrients embedded in ash. Warnock et al. [101] proposed a range of possible mechanisms.

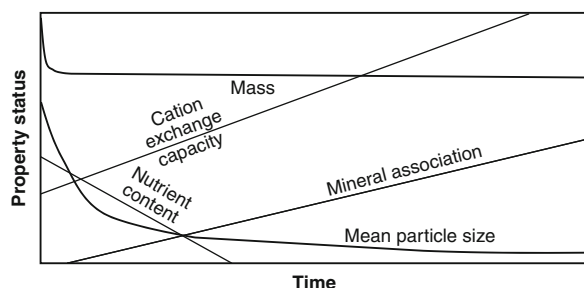
Limitations of Existing Research Base Until recently, there have been no directed research programs to strategically evaluate biochar for its function in soil. Much of the current understanding of the function of biochar rests on published data for charcoal, often in the context of natural systems and wildfire. For reasons highlighted in sections “[Biochar Production](#)” and “[Properties of Biochar](#),” the function of biochar in soil is strongly influenced by feedstock and formation conditions, and charcoal may only provide an insight into some general principles of biochar function in soil. In addition to the problem of extrapolating from studies of charcoal, pilot- and commercial-scale pyrolysis may produce biochar that differs from the products of bench-scale pyrolysis systems operating under ostensibly the same conditions. There is no existing research to evaluate char from gasification, which is likely to provide a function between that of biochar and ash from straight combustion.

Categorization of Current Literature

- *Sediment or soil:* Early evidence for the stability of biochar arose from sediment studies, where

charcoal is preserved under anoxic conditions in which decomposition proceeds inherently slowly [102, 103].

- *Static or dynamic:* Static studies provide snapshot comparisons for a response variable at locations where a relevant soil (or other) variable differs, e.g., presence or absence of vegetation burning history [104, 105]. In a dynamic experiment, a “treatment” is imposed, and change in response variables over a time period determined, or ideally its trajectory observed through intermediate measurement. Chronosequence studies are a variant of the latter that enable long-term dynamics to be studied using samples deemed comparable, aside from the point in history at which the (ideally singular) change or intervention occurred [106–108].
- *Biochar or charcoal:* Natural fire contains an anoxic zone, where biomass pyrolysis prevails over combustion. Natural fire yields low charcoal conversion rates in the range 0.1–5% [109]. Wildfire is typically brief and the peak temperature variable. With rapid heating rates, the conversion may be partial, superficial, or progressive and affected by vegetation moisture content. Wildfire and charcoal are significant considerations in the global carbon cycle, and now an established topic for research.
- Much work on the dynamics of charcoal has been undertaken in this context, and laboratory studies have aimed to mimic wildfire carbonization by exposing biomass to similarly brief, variable, but generally low (ca. 350°C) temperature and semi-oxic conditions, i.e., limited or partial restriction of air flow. Experiments with char produced with complete exclusion of oxygen are much more limited and recent. Published research using char from commercial pyrolysis reactors rather than material produced in a laboratory-scale batch process are very scarce. Only eight studies categorized in [7] used pyrolysis char.
- *Short term or long term:* The various functions of biochar (Fig. 11) may be manifest over different timescales and, crucially, the trajectory of these functions appears to be nonlinear and may not be entirely independent of other functions or the wider system. The average duration of the dynamic studies identified in one literature review [7],



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 11

Schematic to illustrate the challenge of unraveling multiple functions of biochar whose possible trajectories strongly differ

including those undertaken in field plots (but excluding long-term chronosequences), was 11 months. Although the chronosequence approach has been employed to observe the development or demise of functions that change slowly over time (rather than emerge or decline rapidly at the start), few attempts have been made to short cut such change, other than by imposing favorable laboratory-imposed conditions.

- *Gasification or fast or slow pyrolysis:* After oven-drying, plant biomass usually contains about 45% carbon by mass, and a few per cent mineral ash. Ash is broadly conserved, but the proportion of carbon that is retained is specific to the process. Combustion leaves trace amounts of carbon, gasification less than 10%, and pyrolysis typically 30–40%. Ash includes key mineral nutrients such as phosphorus and potassium, other metals and a range of micronutrients concentrated by loss of total feedstock mass in the conversion process [110]. The nutrient value of the products differs markedly on a carbon-mass basis, but in terms of their value to crops will depend not only on rate of char application but on the physical accessibility of nutrients in the char to leaching, plant roots, and mycorrhizal fungi. The production process and feedstock mineral content will also modify the pH of the char by-products, which tend to be moderately to highly alkaline.
- *Feedstock:* Scanning electron microscopy of fresh charcoal and charcoal aged in the natural environment reveals a cellular structure resembling that of

the woody feedstock from which it was derived, e.g., lignified cell walls of dead xylem cells. The structure of char from grass and nonwoody plant material is rarely reported and, similarly, nor is the structure of char produced from digested or composted materials.

- *Tropical or temperate:* Under otherwise equal conditions (moisture, nutrient, and substrate availability), biological activity increases with temperature. Consequently, soils in the tropics tend to be depleted in organic matter and associated biological activity relative to those from temperate regions. In addition, soils that are very old have usually been subjected to extensive weathering and leaching and display low-inherent fertility and are often acidic. Although all functions of biochar may be expressed at all locations, some will be more conspicuous in such soil. In field studies and controlled experiments, half of the research effort has been undertaken in regions with above 20°C mean annual air temperature, and only one fifth in temperate zones below 10°C.
- *Laboratory or field:* Laboratory conditions enable variables and functional attributes to be isolated or controlled, and the impact of climatic variation to be removed. Permutations of different factors are possible since the space and resource requirement may be relatively small and good replication is possible. The interactions between functional attributes of soil and biochar with the wider environment, such as fluctuations in rainfall and evaporation impacting leaching, soil structure, and microbial community composition, can only be assessed in the field. However, the rate at which processes proceed in the field is dictated by the ambient climate and cannot be manipulated. Spatial heterogeneity demands intensive sampling which can constrain experimental design.
- *Soil or soil with plants:* Plants provide a sink for soil nutrients, exert suction on soil pores, and secrete compounds and enzymes that mobilize nutrients and modify soil surfaces. The microbial activity that concentrates around plant roots may “prime” processes that would not otherwise occur, for example, the co-mineralization of recalcitrant biochar and labile glucose [111]. However, the complex soil environment does not comprise such discrete

components and plant-derived substrates are separated by the soil mineral matrix.

- *Empirical (descriptive) or mechanistic (predictive)*: Empirical studies identify statistical relationships between two or more test variables; mechanistic studies seek to understand the reason for such relationships. Mechanistic approaches should offer greater prospect for prediction of effects at other locations, being based on a fundamental understanding of the underlying process. Although technically more robust, mechanistic understanding may take time to acquire and still not be accurate; both approaches require considerable validation especially where multiple variables or processes are involved (Fig. 11).

Extrapolation from Studies of Environmental Charcoal

Given the basic similarity in formation and the relatively abundant literature, it is necessary to view biochar in the context of the existing understanding of charcoal, especially in terms of long-term stability. To date, however, studies that compare char produced under a range of conditions, e.g., varying levels of oxygen exclusion, in terms of agronomy, mineralization, or other parameters relevant to biochar deployment, are lacking. Until these studies have been completed, the congruence in the properties of these materials remains uncertain.

Does charcoal in soil constitute soil organic matter? In the discrimination of more and less recalcitrant forms of organic matter in soil generally, the ratio of oxygen to carbon broadly decreases with age with progressive removal of oxygen through biological or chemical “oxidation.” Charcoal has a characteristically low O:C ratio, while graphitic black carbon (the most stable form derived in combustion) is essentially elemental carbon [112]. By comparison, charcoal and biochar are merely highly depleted in oxygen and hydrogen, containing groups that are strictly organic (most particularly aromatic forms), and part of the soil organic carbon pool.

Can charcoal be distinguished from other soil organic matter? Charcoal is particularly abundant in aromatic carbon that occupies a distinct position in the nuclear magnetic resonance spectrum for carbon (^{13}C NMR), displays a minor depletion in the abundance of the

scarce carbon isotope (^{13}C) relative to other compounds, and is characterized by certain biomarkers (so far, benzene polycarboxylic acid and levoglucosan have been most extensively evaluated). Charcoal is partially resistant to some chemical oxidants typically used to quantify total soil carbon (potassium dichromate), and both chemical and photo-oxidation have therefore been used to quantify it. However, none of these signals have proven entirely exclusive, and the procedures for measurement are complex or slow. Because the functionally relevant level of stability is itself ill-defined or context specific, the analytical separation of charcoal and “ordinary” soil organic matter has yet to be perfected.

What is the historic significance of charcoal in the global carbon cycle? Models describing soil carbon in the agronomic or global change context consider a near-inert soil-carbon fraction to correctly simulate response to altered climate or organic matter inputs, which being site-specific generally reflect, at least in part, contrasting abundance of charcoal in regions where wildfire is more or less frequent. The rate, extent, and completeness of conversion of biomass to charcoal in wildfire is highly variable. Nonetheless, making assumptions about such factors based on available evidence leads to estimates for a mean residence exceeding 1,000 years [113]. Charcoal is thought to account for 1–20% of organic carbon in soils, and at least 150 GtC of the global soil pool comprises charcoal or its more condensed or graphitic relatives, soot and elemental black carbon [11]. This implies that up to 150 Mt of carbon has annually cycled through the biosphere in the formation and degradation of charcoal-derived carbon.

Are the impacts of biochar carbon analogous to those of soil organic matter? Some properties of biochar, and specifically its impacts on physical soil properties, are also associated with bulk soil organic matter. It is not, however, safe to assume that the mechanisms by which these are provided are identical, or that the impacts are equivalent in magnitude, direction, or duration – and thus that biochar can provide a direct substitute for higher levels of other organic matter in soil. This is of practical importance since biochar is carbonaceous and thus not readily distinguished from organic matter using current techniques. This is analogous to the challenge of discriminating chalk and limestone from organic carbon in soil.

Can impacts be predicted from ex situ properties? The ex situ characteristics of organic matter and biochar are unlikely to be additive with respect to a soil's properties. For example, certain soil minerals (clays) have a high cation exchange capacity; although organic matter has higher specific exchange capacity mass for mass, binding between organic and mineral fractions shields exchange sites at the molecular-scale and reduces the sum effect. At the moment, it is not completely clear whether interactions between char and mineral particles will occur significantly at this physical scale or primarily as discrete, disparate particles. Cation exchange capacity of biochar also appears to evolve over time, and it is likely that many other properties have a trajectory which is currently ill-defined.

Evidence to Address Key Questions around PBS

Biochar and Contaminants In terms of human health and the food chain, the irreversibility of biochar addition is a key consideration. Existing soil amendments contain immobile components, albeit in less visible form and biochar inherits the potential risk posed by the feedstock that might otherwise be directly applied (see section “[Properties of Biochar](#)”). However, the class of these compounds known to be formed in the charring process itself (polycyclic aromatic hydrocarbons, PAHs) is process dependent. Without extensive evaluation of pyrolysis char, it is difficult to assess the risk posed by PAHs in PBS specifically as most data available relates to charcoal.

Charcoal is generally produced at lower temperatures that might favor PAH formation, but vapors may combust rather than condense and could thus be eliminated. Levels of extractable PAHs in charcoal are variable, but reported concentrations [114–117] generally fall between those reported for urban and rural soil on a mass basis (see [Table 2](#)). These compounds are persistent but ultimately degradable in soil [50].

The effect of association with chars on rate of degradation of PAHs, and the balance between rates of accumulation and release has not been systematically addressed. Concentrations of PAHs in soils subjected to natural fire suggest, however, that degradation is in excess of sorption. The capacity of both activated and nonactivated charcoal, typically as charcoal from or mimicking natural fire to adsorb PAHs and other

organic contaminants, has been relatively well assessed [118, 119].

Since metals are broadly conserved in pyrolysis, the total metal content of biochar will be determined largely by the feedstock content and the yield of char. The higher the carbon content of the char, the lower will be the mass concentrations of metals. On a biochar mass basis, the metal concentrations in products from gasification where char yield is small (a few to 10%) are likely to be up to tenfold higher than in slow pyrolysis. Data on the availability of metals from charcoal or biochar in soil is lacking. However, the potential for pyrolytic char to remediate land contaminated by metal cations has been demonstrated [120].

Stability of Biochar Carbon About 60% of the literature evaluated in [7] related to the stability of charcoal or to the quantification of char in soil (equally divided). Stability has been addressed both in real-time observation, where sensitivity can be enhanced through isotope tracers [121, 122], or extrapolation from measurements of soils from systems routinely experiencing natural fire [8, 106, 107]. In three cases, the effects of biological activity enhanced by substrate addition have been investigated [108, 111, 122]. Only in one case has pyrolysis char been evaluated [123] and, most often, the feedstock has been wood-derived.

Inference from measurements on soils in systems subject to natural fire suggests millennial stability, and in extrapolation from controlled incubations (elevated temperature and optimal moisture), the general acceleration of mineralization (decomposition) that occurs in such systems has been noted and accounted for [124].

Newly formed char appears to contain a small biologically labile fraction (see below), alkaline pH (mean pH = 8.5; ten studies), and nutrients available in ash from partial combustion embedded in the residual matrix. Only in one published study is this labile fraction deliberately extracted prior to evaluation [125]. Allowing for these characteristics that may lead to nonlinear carbon loss, other deficiencies in laboratory studies (simulation of natural char formation), and effects of induced changes in soil chemistry, the assumption of centennial to millennial stability does not appear unreasonable [122].

Experiments using newly formed charcoal have generally used particles <2 mm diameter (with no minimum particle size), but it has been noted that the physical fate of charcoal is predominantly in fine fractions, broadly <50 μm [90], and that its physical diminution appears relatively rapid, presumably through physical weathering and abrasion. There appears to be substantial evidence for intimate mineral–char interactions which, it has been hypothesized, might guard against degradation; however, discrete char particles have been found to persist within free organic fractions over a period of decades [126].

Three studies found no evidence for a role of tillage in the mineralization of wood-derived charcoal [122, 126, 127], and the single study that has explicitly examined the stability of pyrolytic char from wood and cereal straw suggested a slow and predominantly abiotic degradation which has been convincingly demonstrated for wood charcoal in a climosequence, which confirmed the sensitivity of absolute rates of degradation to temperature [33].

Oxidative measures are one of the key methods used to quantify char in soil, however they are used with the objective of retaining all charcoal in order to identify the wide continuum of char on soil (ranging from black carbon to soot), rather than identifying more or less stable subcomponents. However, the potential to develop artificial aging techniques (that simulate enzymatic oxidative degradation in soils) to rapidly compare and evaluate biochar stability (relative to charcoal) appears to have been rather overlooked and will be useful in seeking greater certainty on this critical matter [113, 112].

Labile Biochar Fractions Incubation of soil with manufactured or un-aged char typically results in higher CO_2 evolution than from the same soil without char. However, the degree of excess declines over time in a strongly nonlinear fashion in the short term [121, 123, 128–130]. This suggests a “priming” of decomposition of carbon, either of that already in the soil, or more likely of carbon in the added char. Priming of existing soil carbon could be a consequence of the modification of the soil-chemical environment (see below), while loss of carbon from biochar can result from the mineralization of a labile char fraction. These patterns also suggest that priming is complex and that extrapolation of stability using short-term decay rates

will be unreliable; such rates are not consistent with the age of charcoal found in archaeological soils such as the *terra preta*. The parameters that govern the balance between labile and stable components are not yet fully understood.

Priming of Soil Carbon or Biochar Loss The potential for biochar, in the form of synthetic charcoal, to cause or accelerate the decomposition of preexisting soil organic matter (priming) has been reported in medium-term study of litter layers in the boreal zone [131]. The loss of litter carbon was measured over a period of 10 years, but almost all the loss occurred prior to the first annual sampling. The litter into which charcoal was introduced was likely to be acidic and nutrient constrained, in which case the decomposition response is expected.

In Canada, and with the benefit of a carbon isotope trace, information on priming in tilled arable soil was obtained on a 65-year timeframe. This indicated that the mean residence time for particulate organic matter in soil increased by a factor of 2.5 at sites where charcoal derived from historic natural fire was present [126]. Another study, also with a carbon isotope trace, suggested slower and less complete utilization (high stabilization) of organic material added to soils from a tropical environment containing aged charcoal [132].

A single laboratory study [111] showed an approximate doubling of charcoal degradation rates (charcoal priming) with the addition of glucose to soil, a compound often used as a simple analogue for the labile carbon exuded into soil by living plant roots. The initial rates of loss were still low (0.5% over 60 days, which is a smaller proportion of charcoal carbon that might reside in a labile charcoal component) – especially for higher temperature char created from wood and for an experiment conducted under optimal conditions in a sand matrix. Quantitative extrapolation of such laboratory studies to the priming that might be likely to occur in the field, particularly with contrasting levels of microbial and plant root activity, is difficult.

It has been noted that if priming of soil organic matter is a permanent function of charcoal, the amount of non-charcoal carbon present under equilibrium field conditions must be lower than in charcoal-free soils [133]. Available data do not support this, and the Amazonian *terra preta* are enriched in organic matter

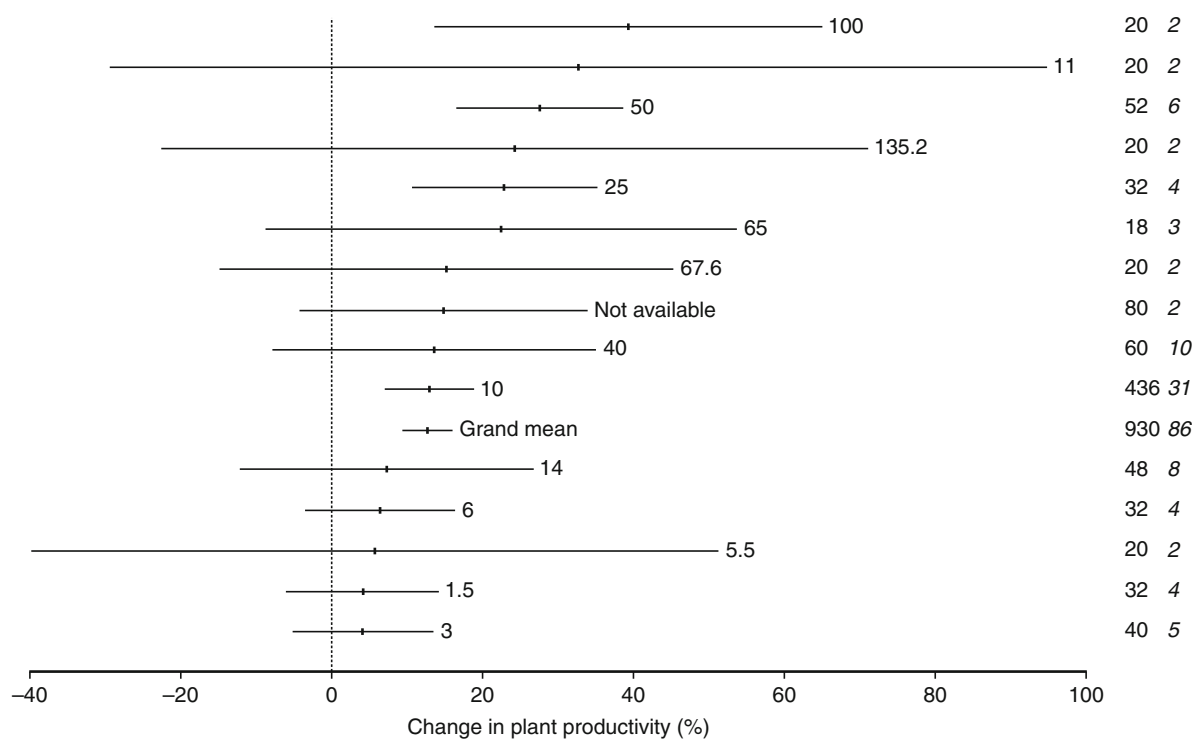
relative to the surrounding soils, as well as containing large amounts of aged charcoal. Due to climatic influences, the Amazonian soils are rather low in organic matter naturally. The likelihood of an analogous accumulation in temperate soils amended with biochar is not certain, given higher background soil-carbon mineralization rates. Other studies have also suggested stabilization of soil organic carbon pools [134] and suppression of CO₂ production in biochar-amended soils [135].

Biochar and Soil Nutrient Dynamics Reported increases in crop yield with charcoal addition have precipitated a number of plot-scale field trials to evaluate impacts on soil fertility, mainly through crop grain or biomass yield, usually with some measure of nutrient uptake. Reviewing 19 relevant articles in the literature [7], none of the reported studies have been

undertaken in temperate zones. As such, caution should be adopted in directly transferring knowledge gained from tropical environments to temperate regions. In the tropical environment, the impacts have generally been positive, though most often in combination with fertilizer nitrogen. Less than one third of these studies have used char application rates of less than 15 tC ha⁻¹, however, and only three used pyrolytic char.

Verheijen et al. [2] undertook a meta-analysis of the effects of biochar addition to soil on crop production using nine studies (all of which used replicates to measure variance), involving 86 separate “treatments”. The results are reproduced in Fig. 12.

The sample means indicate a small, but positive, effect on crop productivity with a grand mean of c. 10%. While there is some apparent trend of increased biochar additions, resulting in higher yields, this is not



Biochar, Tool for Climate Change Mitigation and Soil Management. Figure 12
The percentage change in crop productivity upon application of biochar at different rates from a range of feedstocks along with varying fertilizer co-amendments. *Points* represent mean, and *bars* represent 95% confidence intervals. Numbers next to bars denote biochar application rates (t ha⁻¹). Numbers in the two columns on the right show number of total “replicates” upon which the statistical analysis is based (***bold***) and the number of “experimental treatments” which have been grouped for each analysis (*italics*) (Reproduced with permission from Verheijen et al. [2])

statistically significant at the $P = 0.05$ level as can be seen from the overlapping error bars at the 95% confidence interval. Biochar additions at rates of 10, 25, 50, and 100 t ha^{-1} led to statistically significant increases in crop yields compared to a control with no addition, though other studies using 40 and 65 t ha^{-1} did not show any statistically significant yield increase. Figure 12 illustrates that there is a wide variance in the response to biochar addition, e.g., at the 5.5, 11, and 135.2 t ha^{-1} application rates. Verheijen et al. speculate that the reasons for this are variability in the biochar, crop, and soil types. They also note that the means for each application rate are positive, and that no single biochar application rate had a statistically significant negative effect on crop productivity (though individual experiments have demonstrated negative effects, e.g., [84], [159]). On the other hand, the studies they examined do not cover a wide-range of latitudes and are heavily skewed toward (sub-) tropical conditions.

Substituting chemical fertilizer for the nutrients added into the soil as biochar has not resulted in the same increase of crop productivity as provided by biochar addition. In two cases where the effect of pH modification was controlled for by liming, the effect of char was still superior [7]. This suggests that char might impact crop growth through its impacts on soil physical properties and/or on mediation of nutrient exchange between soil and plant.

In classic studies of *terra preta* fourth-season maize yields were much higher in plots amended with char and fertilizer than the non-fertilized and non-char amended control [136], and similar results have been shown in experiments with maize carried out in Columbian savannah soil [137]. However, regarding the *terra preta* studies, it is strictly incorrect to say that the effect of the treatments was to increase yield, since the yields for all treatments displayed post-clearance decline, and the control yields were ultimately very low.

Limited evidence under tropical soil conditions suggest that the addition of fresh charcoal can reduce nitrogen leaching loss. Soils with higher and long-established charcoal content had enhanced nutrient status but leached extra added nitrogen [1]. There is a relatively large amount of consistent evidence for the partial surface oxidation of char by chemical and

biological processes in soil and proliferation of carboxyl groups [138]. It appears that this is reflected in the cation exchange capacity of aged charcoal and charcoal-rich soils, but not shown in new char. Plot-scale experiments indicate that the uptake of other nutrients may be enhanced by charcoal, in particular phosphorus as ash in charcoal may be more available than phosphate in the soil.

Since biochar has a high carbon-to-nitrogen ratio, it is likely that rapid mineralization of a labile carbon fraction could – by immobilization – contribute to a draw on soil mineral nitrogen, in addition to an effect of ammonium sorption, and potentially reduce crop nitrogen supply. Evidence for this effect is relatively abundant and consistent in the literature, but the effect depends on the status of indigenous soil mineral nitrogen, and these studies have been undertaken exclusively in the tropics.

Immobilization tends to enhance soil nitrogen supply to the crop in the longer term since microbial proliferation builds a reservoir of mineralizable nitrogen. In field studies of charcoal or biochar extending beyond a single season, this effect may be observed, where second- or subsequent-season (but not first-season) are elevated relative to non-amended controls.

Biochar and Emission of Nitrous Oxide and Methane from Soil

A single peer-reviewed study reports suppression of nitrous oxide emission from soil from charcoal [125]; however, in the light of the importance of N_2O emissions to total agricultural greenhouse gas emissions and emerging evidence reported in recent studies (e.g., [13, 139, 140, 141]) the effect warrants further attention. Results from planted fields in Columbia showing a large positive effect are unpublished [142] as are three studies showing conflicting outcomes in laboratory studies using soils from Australia [143, 144] and New Zealand [139]. Laboratory studies used high rates of application [125, 135], single soils [145], or single types of charcoal. Results from a laboratory study using biochar made from poultry manure and *Eucalyptus* wood showed N_2O emissions were reduced over a long-term (5-months with three wet-dry cycles) period [140].

Nitrous oxide is emitted mainly by specific groups of bacteria, which under anaerobic conditions reduce nitrate rather than oxygen (nitrate to N_2O via nitrite

and nitric oxide). Emission of N_2O at low rates may also occur under aerobic conditions from the activity of chemotrophic bacteria converting mineralized organic nitrogen (ammonium) to nitrate. Higher soil organic matter increases nitrification, but the application of nitrogen fertilizer has a greater immediate impact on soil nitrate concentrations and, hence, N_2O emission.

Proposed mechanisms for biochar suppression of N_2O revolve around modification of soil-water dynamics, e.g., drawing soil solution and dissolved nitrate into inaccessible pores (small pores saturating first) and maintaining aerobicity in inhabited soil-pore space; increase of soil pH which under anaerobic conditions favors completion of nitrate reduction to N_2 from N_2O ; or the adsorption of ammonium and its protection from nitrification and denitrification [125, 145, 146]. Singh et al. [140] also propose the importance of time-induced changes (“aging”) on biochar properties which were attributed to the reduction in ammonium leaching and N_2O emissions they observed.

The effect of water addition cannot be completely evaluated under constant conditions, but Yanai et al. [125] found suppression was reversed when water-filled pore space was increased from partial to near-complete saturation. In the same study, the addition of combustion ash to the soil, separately from charcoal, did not suppress emission. However, [140] and [147] have demonstrated reduced N_2O emissions after a sequence of wet-dry cycles. Therefore, there is the important influence of time which must be taken into consideration. Simultaneous monitoring of N_2 is also required to confirm N_2O reduction. It has also been shown that nitrate has also been reported to accumulate where N_2O is suppressed [147].

Mobility of Char Biochar and charcoal fines have a low bulk density of approximately 300 kg m^{-3} against a typical soil bulk density of $1,300 \text{ kg m}^{-3}$. Particles may be very fine in size and, in addition, surfaces may be hydrophobic [148]. Collectively, these characteristics indicate a higher potential for lateral transfer in water than for other soil components [149], and applied at a high rate in tropical environments subjected to frequent intense rainfall, erosion of charcoal off-site has been measured in proportions up to 25% in 2 years [150], and most of the 66% loss

calculated by Nguyen et al. [106] in 30 years after surface deposition was attributed to erosion.

Negligible longer-term losses [106] and low rates of movement apparent for natural charcoal in a temperate environment [126] suggests a rapid decline in hydrophobicity, physical breakdown, and development of association with mineral particles [87, 151, 152]. The “anchoring” of particles within the soil matrix at depth may be critical in limiting erosion. The apparent combustion of fire-derived char in dry regions, where material remains at the surface between fires [153, 154], emphasizes the role of incorporation into deeper soil in ensuring longevity in the natural environment, and that in more biologically active soils, this must therefore occur. However, measured rates of transport into subsoil appear to be slow [150].

Meanwhile, studies of the global cycle of “black carbon” have established the existence of significant flux from land to ocean at a macroscale [102, 155]. Little literature has addressed the process of transport of char through the environment, although it has been noted that PAH is high in organic matter dissolved in alkali extracts after natural fire [156].

Char, Soil-Water Dynamics, and Irrigation In large quantities, wood-derived charcoal modifies soil physical properties. It has a low-inherent bulk density of $0.3\text{--}0.5 \text{ t m}^{-3}$, which is one third to one fifth that of typical NW European arable soil. Depending on particle-size distribution of the char relative to that of the soil and the extent to which added char may locate within existing pores, higher experimental rates of application could directly reduce soil bulk density and increase soil volume. This affects water-holding capacity and water-filled pore space, but declining hydrophobicity and the effects of weathering on particle size will determine the duration of this effect. In the experimental context, water-holding capacity is measurably increased by adding fresh charcoal and must be considered in the design of laboratory soil incubations [132]. Studies of amended soils can be adjusted for either equal gravimetric water content, or to equal tension (depending on the hypothesis). Water storage could be of critical value, yet the factors that determine the efficacy of char in this context have not been clarified.

Published evidence [88] for the effect of biochar on pore-size distribution, however, is remarkably scarce.

Some assessments have been made, and the problem appears to be in the level of replication required to demonstrate significant affects using methods best used in comparison of different soils. One study [157] has reported water-holding capacity of soils amended at low, medium, and high rates with pyrolytic char; one study has focused solely on pore-size characteristics of charcoal and pyrolytic char [88]; and one has measured the impact of charcoal residues on water-holding capacity at old kiln sites [83].

Summary

The evidence for the function of biochar in soil is based largely on evidence from studies of charcoal, and predominantly in the tropical environment. Triangulation of existing knowledge with systematic studies of biochar produced using technology and feedstocks relevant to viable temperate systems is needed, combined with techniques to rapidly assess long-term stability, and potential soil agronomic benefits.

Conclusion: Evaluating the Sustainability of Pyrolysis-Biochar Systems

A *sustainable biochar system* can be defined as one which: (a) produces and deploys biochar safely and without emitting non-CO₂ greenhouse gases; (b) reduces net radiative forcing; (c) does not increase inequality in access to and use of resources unduly, and (d) provides an adequate return on investment. Condition (a) is important to ensure that PBS technologies and practices do not pose undue risks to human health and safety and the environment (e.g., through inhalation of dust, biochar particles turning waterways or surrounding vegetation “black,” adding N₂O, CH₄, or black carbon soot particles to atmosphere increasing net greenhouse forcing, etc.). Condition (b) is important to ensure that the net result of a PBS is indeed to reduce net radiative forcing relative to a baseline case. This is primarily due to reduction in atmospheric concentration of greenhouse gases through removal and avoided emissions. Condition (b) also takes account of direct and indirect land-use changes (I/LUC), which can result in one-off emission of hundreds of tons of carbon per hectare in the case of tropical and peatland rainforest. Clearing of Brazilian wooded *cerrado* incurs a carbon loss of c. 45 tC ha⁻¹, US

grassland c. 30 tC ha⁻¹, and abandoned US crop land zero or only a few tons per hectare [160]. Clearly, there is no point in converting land that incurs a large loss of carbon to biomass production for energy if the main purpose (or a large part of the rationale) of a project is to abate carbon through biochar production.

Condition (c) is relevant because an increase in demand for biomass will have knock-on impacts upon other users or potential users of that biomass, or upon other biomass, demand for which increases due to substitution effects. This also relates to LUC and ILUC, which frequently encounters equity and justice problems and questions. Condition (d) refers to economic viability since in market economies investment will only follow favorable rates of return. Defining an “adequate rate of return” is fraught with difficulties and depends upon subjective considerations such as the discount rate selected.

Systems which meet all of the above criteria do not exist at demonstration or commercial scale at the current time, and do not include traditional charcoal production. This is not surprising, of course, because biochar has only been proposed as a carbon abatement and agronomic improvement technology since the early- to mid-2000s. The further development and eventual deployment of biochar will be driven by one or more of the following policy and economic drivers.

- (a) *Agronomic value of the biochar*: This value could be quite large on depleted soils, but any value has to be offset against the costs of production, delivery, and application to soil. Where the biochar is a by-product of electricity (or heat) generation, it may have a zero production cost. Examples of zero-cost biochar are few and far between and unlikely to be the norm. The cost of biochar production will, in many cases, be hard to recoup from the value of the agronomic gain alone.
- (b) *Carbon storage value of the biochar*: If biochar can be ascribed a carbon storage value, this could greatly accelerate its successful take-off. The difficulty in ascribing a carbon value to biochar relates to the scientific uncertainty over long-term stability and interactions with soil organic carbon, lack of agreement on (and difficulty relating to) inclusion of land-based carbon budgets in trading arrangements, and technical uncertainties around

Monitoring, Verification, Accounting, and Reporting (MVAR).

- (c) *Waste management*: If pyrolysis-biochar systems are a cost-effective way of dealing with certain organic waste fractions (relative to other disposal/management options), this could drive the deployment of PBS through the value of the avoided tipping-fees to waste-management companies. The difficulty of this route is that waste biochar products are likely to pose more environmental and health and safety risks and will need to be carefully assessed and controlled. Such regulation is likely to drive-up the costs of biochar from wastes and to increase the regulatory barriers and hurdles, reducing interest from the industry. Furthermore, tipping fees are related to land-fill costs and taxation, which are subject to political change.
- (d) *Renewable energy incentives*: To make pyrolysis-biochar add-up, it is likely that incentives will be required for the generation of renewable electricity and/or heat. Where the incentives are for electricity generation, however, other thermal conversion technologies such as combustion and gasification (with limited char production) will frequently have a competitive edge. Such incentives and subsidies are also vulnerable to political change.
- (e) *Agri-environmental policies*: Another potential route to biochar deployment is through appropriate agri-environmental policies. If biochar addition can be demonstrated to have multiple benefits to agricultural land, agricultural support policies could be used to promote its adoption, for example, through inclusion in measures that are eligible for area-based and environmental stewardship payments.

One way forward in the short- to medium-term is to promote the use of biochar in particular niche applications, where its potential can be demonstrated and from there broader applications identified. This is broadly consistent with the innovation studies literature on socio-technical transitions: new technologies nearly always begin as niche applications that, if useful, find a wider role (3). The identity of the niche application will vary, depending on local, national, and regional context; policy; and socioeconomic drivers and incentives. In Europe, it may be sustainable biochar

production from particular organic waste streams (paper or sewage sludge, for example), while in Asia, it may be carbonized rice husks from a gasifier as described in Box 2. In North America and Scandinavia, woody wastes from the timber industry may be ideal feedstocks, while in Africa, agricultural residues that would otherwise be burnt may offer-up opportunities.

Future Directions for Research, Development, and Demonstration

Biochar is a complex, multifunctional material that requires improved mechanistic knowledge and understanding – of its production, properties, impacts, interactions, costs, and benefits. Without this mechanistic process understanding, it is difficult if not impossible to predict and assess accurately the benefits of biochar for either greenhouse gas abatement or for addition to the soil even with evidence from individual field trials. We have identified the key research needs according to three broad headings below.

Pilot Production Research Facilities for Biochar and “Engineered” Biochar

What is the need? A strategic approach to producing, testing, and comparing biochar samples from different technologies, under specific reproducible conditions, would improve the evidence base. Facilities are needed to serve the research community, focusing current and future effort away from charcoal and toward biochar, produced from designated feedstocks under highly specified process conditions.

Why? The engineering and technological challenges are intimately related to the engineered biochar concept – namely engineering biochar with specific and controlled properties, designed for particular purposes (e.g., carbon abatement, short- and long-term agroeconomic gain, waste-management and pollution control, energy production, etc.) and contexts of application (soil types, agricultural systems, other land-uses, etc.).

When? The need is urgent if biochar is to have a role in tackling climate change in the next several decades and necessary for any future soil application of biochar.

Resource implications: The resources required are reasonably large, but not large compared to much technology-development since biochar can be

produced at small-scales using relatively straightforward equipment.

How well advanced is existing research? There is currently limited activity or capacity anywhere in the world for technological evaluation of biochar production.

Ability to address key questions: Once equipment is in place, it should be relatively straightforward to address the key questions which arise, though some issues will inevitably take time to answer.

Examples of key questions to address:

Recipes for producing engineered biochar with specific properties and functions – acquiring the technological know-how to produce biochar with defined properties based upon a process understanding of production conditions.

Better understanding of the carbon and energy balance of alternative biochar production technologies – as yet there is little consistent and high-quality data on pilot- and commercial-scale pyrolysis (especially slow and intermediate) without which any evaluation of biochar is impaired.

Better understanding of the superlabile, labile, and stabilized components of biochar – better knowledge of what influences the Carbon Stability Factor for biochar is required, along with the effects in soil and field of labile versus stable carbon.

The Predictability and Certainty of the Impacts of Biochar

What is the need? If biochar is to be a commercial proposition, it will be necessary for reliable predictive knowledge of its impacts in particular soil and agro-economic contexts to be well established (just as is the case for chemical fertilizers or pesticides). There is also need for a practical and scalable method by which the stable component of biochar can be established experimentally through acceleration of initial degradation as well as for examining the change that occurs soon after incorporation in soil.

Why? Only if the user is confident of positive and cost-effective benefits of biochar, when applied at particular rates, will a biochar market emerge. If the purpose is solely carbon storage, then the key issue will be long-term stability of the biochar.

When? For the purposes of carbon storage, urgent knowledge of long-term stability will be necessary. Predictive knowledge of soil and plant impacts is necessary for development of a market for biochar addition to land.

Resource implications: the resources required are moderate, but progress is being held back by lack of samples and equipment.

How well advanced is existing research? Evidence for the stability of charcoal in agriculture and the wider environment has been inferred in detailed studies in the USA and Australia. Work on the definition and stability of biochar is ongoing by established research groups. Work on soil and plant effects is well established internationally (especially in the USA, Australia, Brazil and Japan). However, this research is still in its infancy with no systematic effort: the opportunity exists for a focused and deterministic approach.

Ability to address key questions: In principle, it should be possible to address the stability question relatively quickly. Addressing the soil and plant effects will be more complex and time-consuming because of variability and complexity.

Examples of key questions to address:

These questions/topics can be addressed/answered fairly quickly.

Short- and long-term effects – separating out the long-term and short-term effects of biochar by comparing the functions of fresh and artificially aged material

Available nutrients and contaminants – Agreement on a methodology to quantify “available” nutrients and contaminants in a biochar matrix.

Deployment equipment and appliances – Develop modifications of existing agricultural equipments and implements so as to develop effective and efficient ways of storing and deploying biochar in realistic farm-based scenarios.

Biochar in grassland systems – The potential to reduce methane emissions from cattle, biochar as a slurry additive for odor control, etc.

Methodologies for evaluating the migration of biochar by movement through the soil profile, wind-erosion, water-erosion, etc. – necessary for regulation and carbon accounting.

Low-cost monitoring of biochar – Investigation of field spectroscopy and remote sensing for the low-cost monitoring of biochar added to soil.

These questions/topics are more difficult, complex, and/or simply time-consuming, and will take longer to address or answer

Nitrous oxide suppression – Examination of the mechanism by which biochar, at least under certain conditions, can suppress nitrous oxide emission from soil.

Field experimentation and trials strategy – Field experiments and trials that encompass diverse rotations and systems (arable, horticulture, and grassland) and including feedstocks derived from (inter alia) agricultural residues.

The value of biochar-based soil management – Compare the likely value of biochar-based soil management against the return that has been established for active use of other organic resources in management of soil.

Biochar for the control of diffuse pollution – More research on the ability of biochar to reduce leaching from land (e.g., using buffer ditch experiments) or from other sources (e.g., waterways, road surfaces).

Wider Biochar Sustainability Issues

What is the need? What are the wider impacts of biochar as a system, potentially deployed at different scales and in different spatiotemporal and socioeconomic contexts? How can the biochar system be made sustainable?

Why? Pyrolysis biochar systems (PBS), or variants thereof, only make sense if they meet minimum sustainability requirements (standards) and avoid incurring adverse environmental, social, or economic impacts. Sustainability appraisal methods can be utilized to ensure that biochar at a system level “adds-up”

When? It is important to understand system level impacts as these help direct more basic research and development by identifying key sensitivities. It is necessary to evaluate system-level effects prior to real-deployment to understand knock-on effects and potential problems.

Resource implications: The resources required are small compared to the technological and basic

scientific research and development required because equipment and experimental costs are typically lower.

Ability to address key questions: Rapid progress can be made once resource is available, though accuracy and precision is dependent upon the availability of new data from technological and natural scientific R&D.

Examples of key questions to address:

Better Life-Cycle Assessments of pyrolysis-biochar systems – improved data across the whole PBS supply chain (from feedstock to field) and alternative biochar-producing systems.

Better techno-economic cost modeling – using more accurate data and with an improved representation of the key processes and stages, including production, distribution, storage, and deployment.

Better comparative analyses of biochar versus other resource-use options – need for explicit and transparent comparisons using best-available data of the most effective way of using and managing limited biomass resources for, e.g., bioenergy generation, carbon/greenhouse gas abatement, sustainable soils and waste management, composting and sustainable agri-food systems.

Assessment of land-use implications of biochar deployment – how biochar might influence the competitive advantage of different crops and the knock-on impacts on land-use decisions, supply, and demand.

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Bioclimatic Design

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Article Outline

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Glossary

Absolute humidity Absolute humidity is defined as the weight of water vapor contained in a unit volume of air. Typical units are pounds of water per pound of dry air or grains of water per cubic foot. Absolute humidity is also known as the water vapor density (D_v).

Celsius temperature ($^{\circ}\text{C}$) Celsius temperature ($^{\circ}\text{C}$) refers to temperatures measured on a scale devised in 1742 by Anders Celsius, a Swedish astronomer. The Celsius scale is graduated into 100 units between the freezing temperature of water (0°C) and its boiling point at normal atmospheric pressure (100°C) and is, consequently, commonly referred to as the *centigrade scale*.

Dew-point temperature (DPT) Dew-point temperature (DPT) is the temperature of a surface upon which water vapor contained in the air will condense into liquid water. Stated differently, it is the temperature at which a given quantity of air will become saturated (reach 100% relative humidity) if chilled at constant pressure. It is thus another indicator of the moisture content of the air. Dew-point temperature is not easily measured directly; it is conveniently found on a psychrometric chart if dry-bulb and wet-bulb temperatures are known.

Dry-bulb temperature (DBT) Dry-bulb temperature (DBT) is the temperature measured in air by an ordinary (dry bulb) thermometer and is independent of the moisture content of the air. It is also called “sensible temperature.”

Fahrenheit temperature (F) Fahrenheit temperature (F) refers to temperature measured on a scale devised by G. D. Fahrenheit, the inventor of the alcohol and mercury thermometers, in the early eighteenth century. On the Fahrenheit scale, the freezing point of water is 32°F and its boiling point is 212°F at normal atmospheric pressure.

Humidity Humidity is a general term referring to the water vapor contained in the air. Like the word “temperature,” however, the type of “humidity” must be defined.

Relative humidity (RH) Relative humidity (RH) is defined as the percent of moisture contained in the air under specified conditions compared to the amount of moisture contained in the air at total saturation at the same (dry-bulb) temperature. Relative humidity can be computed as the ratio of existing vapor pressure to vapor pressure at saturation, or the ratio of absolute humidity to absolute humidity at saturation existing at the same temperature and barometric pressure.

Water vapor pressure (P_v) Water vapor pressure (P_v) is that part of the atmospheric pressure exerted due to the amount of water vapor present in the air. It is expressed in terms of absolute pressure as inches of mercury (in. Hg) or pounds per square inch (psi).

Wet-bulb temperature (WBT) Wet-bulb temperature (WBT) is an indicator of the total heat content (or enthalpy) of the air, that is, of its combined sensible and latent heats. It is the temperature measured by a thermometer having a wetted sleeve over the bulb from which water can evaporate freely.

Definitions

Bioclimatic design – combining “biology” and “climate” – is an approach to the design of buildings and landscape that is based on local climate. The approach was promoted in a series of professional and popular publications in the 1950s [1, 2]. In using the term “bioclimatic,” architectural design is linked to the physiological and psychological need for health and comfort. In adopting bioclimatic approaches, the designer endeavors to create comfort conditions in buildings by understanding the microclimate and resulting design strategies that include natural ventilation, daylighting, and passive heating and cooling. The premise of bioclimatic design is that buildings utilize natural heating, cooling, and daylighting in accordance with local climatic conditions.

Resilient design is an extension of bioclimatic design. It adds precautionary measures to provide health and safety to prepare for natural disasters, including extreme storms and flooding of inland watersheds and coastal areas. The concept of resiliency applies lessons from natural systems to design for extreme conditions using strategies found in natural systems, such as buffering, zone separation, redundancy, rapid feedback, and decentralization.

Introduction

Bioclimatic design had been part of practical knowledge of indigenous building throughout historical periods, including early modern architecture. When air-conditioning systems became widely available at the end of the 1950s, interest in bioclimatic design became less evident in professional and popular literature and in built work. The topic reemerged in response to energy shortages of the 1970s – when “passive solar design” became the popular term to describe the approach, at first emphasizing solar heating but soon broadened to passive cooling and daylighting.

With the emergence of global environmental concerns of the 1990s – recognizing that energy conservation has “cascading” effects and benefits in reducing pollution and in mitigating global warming – the scope of bioclimatic design was enlarged to include landscape, water, and waste nutrient recovery. *Sustainable design* of architecture and communities emerged as an approach to protect and improve the biological health of communities conceived as the ecology of building, site, and region.

Some bioclimatic design techniques – earth sheltering is an example – can contribute to comfort and reduce both heating and cooling loads year round. Other techniques are useful only part of the year. The effectiveness of passive solar heating, for example, is very specific to the need for heating and otherwise needs to be tempered by sun shading and thermal mass. Natural ventilation can provide comfort in all seasons, especially in summer when it can reduce or eliminate the need for air-conditioning in some climates.

All buildings experience interruptions of conventional energy availability, often coincident with weather extremes and natural disasters. A precautionary approach to the design of all buildings is to provide bioclimatic means to insure subsistence levels of heating, cooling, and daylighting for comfort, health, and safety in case all power sources are interrupted. For the longer term, in which conventional energy shortages and emergencies are unpredictable, buildings without natural heating, cooling, and lighting impose serious liabilities on occupants and owners.

Strategies of Bioclimatic Design

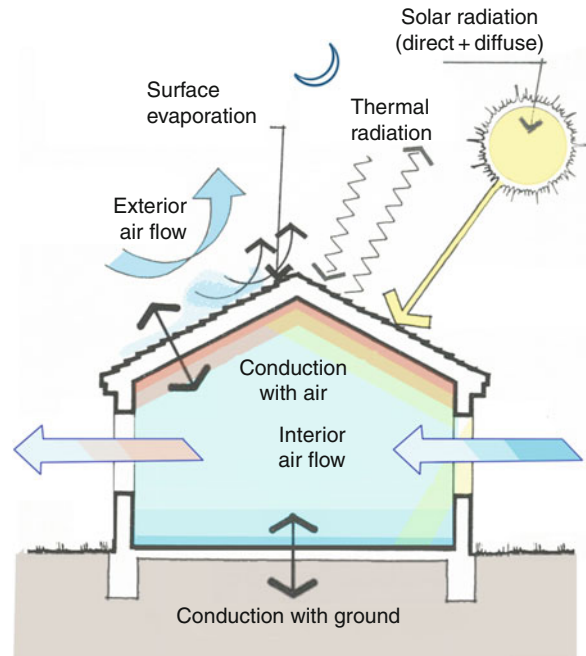
Bioclimatic design strategies are effective for “envelope-dominated” structures – such as homes

and one- or two-story facilities – to provide a large portion if not all of the energy required to maintain comfort conditions.

“Internal load dominated” buildings – such as hospitals, offices, commercial kitchens, and windowless stores – experience high internal gains imposed by the heat of occupancy, lights, and equipment. In such cases, the external climatic conditions may have less influence on achieving comfort and low energy utilization. However, as internal loads are reduced through energy-efficient design – such as low-wattage lighting, energy-efficient equipment, occupancy scheduling and zoning – the effects of climate become more obvious and immediate. All buildings can benefit from available daylighting, but large glazed areas require careful shading control, glazing selection, and possibly night insulation.

The “resources” of bioclimatic design are the natural flows of energy in and around a building – created by the interaction of sun, wind, precipitation, vegetation, temperature, and humidity in the air and in the ground. In some instances, this “ambient energy” is useful immediately or can be stored for later use. There are definable “pathways” by which heat is gained or lost between the interior and the external climate in terms of the classic definitions of heating energy transfer mechanics. From these, the resulting bioclimatic design strategies can be defined (Fig. 1 and Table 1).

- **Conduction** – from hotter objects to cooler objects by direct contact.
- **Convection** – by flow of air between warmer objects and cooler objects.
- **Radiation** – from hotter objects to cooler objects within the direct view of each other regardless of the temperature of air in between, including radiation from sun to earth.
- **Evaporation** – the change of phase from liquid to gaseous state: The sensible heat (dry-bulb temperature) in the air is lowered by the latent heat absorbed from air when moisture is evaporated.
- **Thermal storage** – from heat charge and discharge both diurnally and seasonally, as a function of its specific heat, mass, and conductivity. Although not usually listed alongside the four classic means of heat transport, this role of thermal storage is helpful in understanding the heat transfer physics of building climatology.



Bioclimatic Design. Figure 1

Paths of energy exchange at the building microclimate scale.

Bioclimatic design is based upon understanding energy flows within and around buildings (Watson and Labs [13])

In winter (or underheated periods), the objectives of bioclimatic design are to resist loss of heat from the building envelope and to promote gain of solar heat. In summer (or overheated periods), these objectives are the reverse, to resist solar gain and to promote loss of heat from the building interior. The strategies can be set forth as:

- **Minimize conductive heat flow.** This strategy is achieved by using insulation. It is effective when the outdoor temperature is significantly different, either lower or higher, than the interior comfort range. In summer, this strategy should be considered whenever ambient temperatures are within or above the comfort range and where natural cooling strategies cannot be relied upon to achieve comfort (i.e., whenever mechanical air-conditioning is necessary).
- **Delay periodic heat flow.** While the insulation value of building materials is well understood, it is not as widely appreciated that building envelope materials also can delay heat flows that can be used to

Bioclimatic Design. Table 1 Strategies of bioclimatic design (Watson and Labs [13])

Bioclimatic design strategy	Predominant season ^a	Process of heat transfer			
		Conduction	Convection	Radiation	Evaporation
Minimize conductive heat flow	Winter and summer ^b	√			
Delay periodic heat flow	Winter and summer	√		√	
Minimize infiltration	Winter and summer ^b		√		
Provide thermal storage ^c	Winter and summer	√	√	√	
Promote solar gain	Winter			√	
Minimize solar gain	Summer			√	
Minimize external air flow	Winter		√		
Promote ventilation	Summer		√		
Promote radiant cooling	Summer			√	
Promote evaporative cooling	Summer				√

^aProperly described as “underheated” and “overheated”

^bIn overheated periods where air-conditioning is required

^cThermal storage may utilize “phase change” materials and the latent heat capacities of chemicals such as eutectic salts

improve comfort and to lower energy costs. Time lag through masonry walls, for example, can delay the day’s thermal impact until evening and is a particularly valuable technique in hot arid climates with wide day-night temperature variations. Techniques of earth sheltering and berming also exploit the long-lag effect of subsurface construction.

- *Minimize infiltration.* “Infiltration” refers to uncontrolled air leakage around doors and windows and through joints, cracks, and faulty seals in the building envelope. Infiltration (and the resulting “exfiltration” of heated or cooled air) is considered the largest and potentially the most intractable source of energy loss in a building, once other practical insulation measures have been taken.
- *Provide thermal storage.* Thermal mass inside of the insulated envelope is critical to dampening the swings in air temperature and in storing heat in winter and as a heat sink in summer.
- *Promote solar gain.* The sun can provide a substantial portion of winter heating energy through elements such as equatorial-facing windows and greenhouses that include other passive

solar techniques which utilize spaces to collect, store, and transfer solar heat.

- *Minimize solar gain.* The best means for ensuring comfort from the heat of summer is to minimize the effects of the direct sun by shading windows from the sun, or otherwise to minimize the building surfaces exposed to the summer sun by use of radiant barrier and by insulation.
- *Minimize external air flow.* Winter winds increase the rate of heat loss from a building by “washing away” heat and thus accelerating the cooling of the exterior envelope surfaces by conduction, and also by increasing infiltration (or more properly, exfiltration) losses. Siting and shaping a building to minimize wind exposure or providing wind-breaks can reduce the impact of such winds.
- *Promote ventilation.* Cooling by air flow through an interior may be propelled by two natural processes, cross-ventilation (wind driven) and stack-effect ventilation (driven by the buoyancy of heated air even in the absence of external wind pressure). A fan (using photovoltaic for fan power) can be an efficient way to augment natural ventilation cooling in the absence of sufficient wind or stack-pressure differential.

- *Promote radiant cooling.* A building can lose heat effectively if the mean radiant temperature of the materials at its outer surface is greater than that of its surroundings, principally the night sky. The mean radiant temperature of the building surface is determined by the intensity of solar irradiation, the material surface (film coefficient), and by the emissivity of its exterior surface (its ability to “emit” or reradiate heat). This contributes only marginally, if the building envelope is well insulated.
- *Promote evaporative cooling.* Sensible cooling of a building interior can be achieved by evaporating moisture into the incoming air stream (or, if an existing roof has little insulation, by evaporative cooling the exterior envelope such as by a roof spray). These are simple and traditional techniques and most useful in hot-dry climates if water is available for controlled usage. Mechanically assisted evaporative cooling is achieved with an economizer-cycle evaporative cooling system, instead of, or in conjunction with, refrigerant air-conditioning.

Bioclimatic Analysis

Analysis of climatic data is a first step in bioclimatic design. Preliminary design direction and rules of thumb can be determined by graphing bioclimatic data. While the method can be done by hand, computer-assisted methods allow this approach to be increasingly accurate.

Humans are comfortable within a relatively small range of temperature and humidity conditions, roughly between 68°F and 80°F (20–26.7°C) and 20–80% relative humidity (RH), referred to on psychrometric charts as the “comfort zone.” These provide a partial description of conditions required for comfort. Other variables include environmental indices – radiant temperature and rate of airflow – as well as clothing and activity (metabolic rate). While such criteria describe relatively universal requirements in which all humans are “comfortable,” there are significant differences in and varying tolerance for discomfort and conditions in which stress is felt, depending on age, sex, health, cultural conditioning, and expectations.

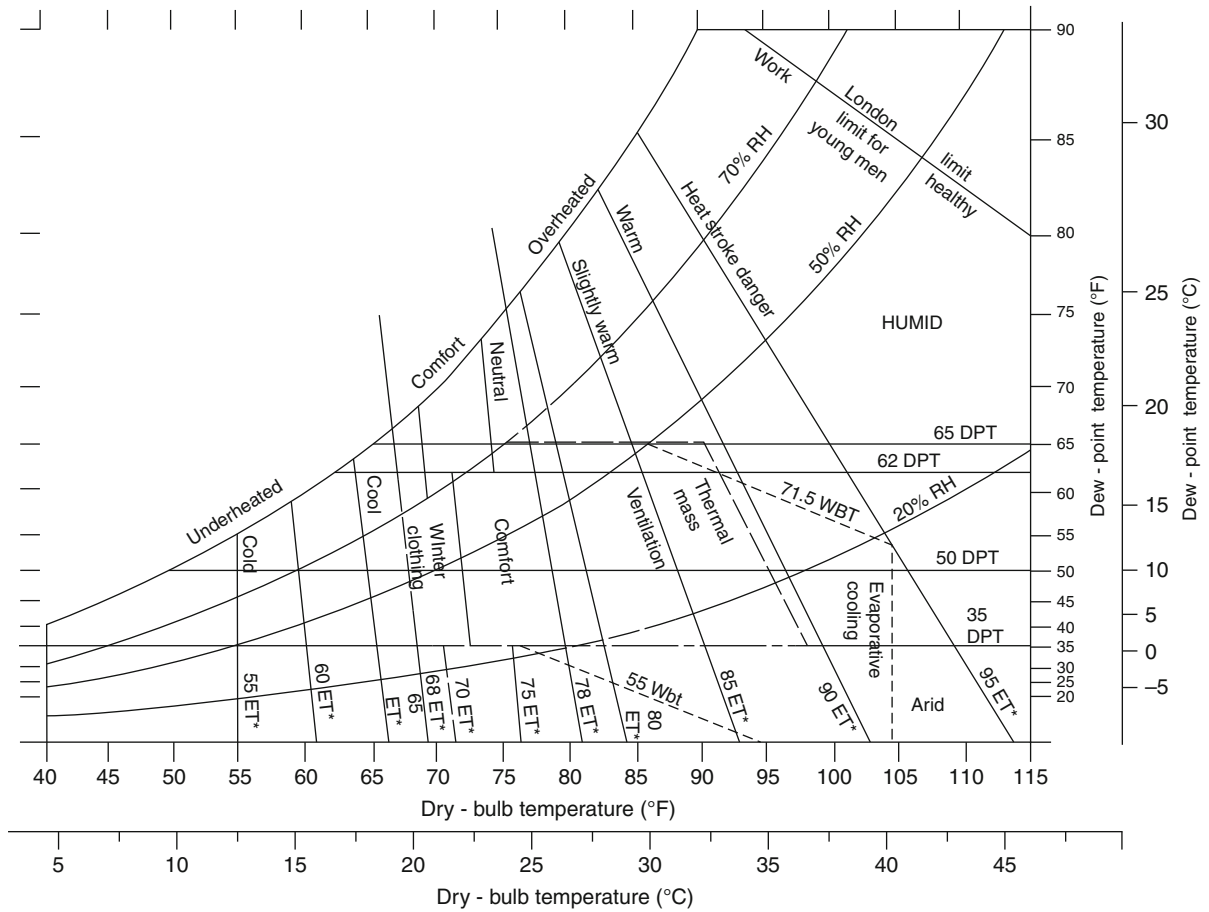
Givoni [3] and Milne and Givoni [4] proposed a design method using the building bioclimatic chart, modified by Arens [5] (Fig. 2). The chart adopts the

psychrometric format, overlaying it with parameters for the appropriate bioclimatic design techniques to create human comfort in a building interior. If local outdoor temperatures and humidity fall within specified zones, the designer is alerted to opportunities to use specific bioclimatic design strategies to create effective interior comfort.

Computer-based simulation and energy design tools make it possible to utilize site-specific hourly weather data to analyze data for bioclimatic design. This makes it possible to compare bioclimatic design strategies for a given climate, comparing a proposed design with a “base case,” that is, the same building without a proposed design feature, such as south-facing glass, added insulation, shading, ventilation, and thermal mass.

Figure 3 depicts a simulated “representative winter week” (7 days) comparison of a “base case” house with a combined set of options, including solar-oriented windows (while decreasing windows on other orientations), increased insulation including nighttime curtains, and interior thermal mass. The “base case” house represented the US code-compliant national average construction, published by the National Association of Home Builders. Bioclimatic design strategies were added as achievable within a 5% increase in construction cost. The “representative winter week” represented a 30-year average winter week (November to January) in which 3 days of clouds were followed by 3 days of sunshine. Heat gains in Btu are indicated above the horizontal bars, and losses below it. The illustration indicates the benefit of the “solar pulse,” that is, passive solar gain in the 3 sunny days at the end of the 7 days (lower right), compared to negligible solar benefit in the Base case during the same sunny period (upper right). In this particular week, the combined passive strategies accomplished a 38% in energy requirement.

The example in Fig. 3 was part of a research project that compared a variety of bioclimatic features, singly and together, in 20 US cities [6]. The results supported several conclusions. Firstly, the relative effectiveness of any particular bioclimatic design technique is more than additive, that is, when combined they supported larger efficiencies in performance than when used singly. Secondly, when compared in different climatic zones, the rank order of most effective strategies changed – perhaps obvious, but worthy as



Bioclimatic Design. Figure 2

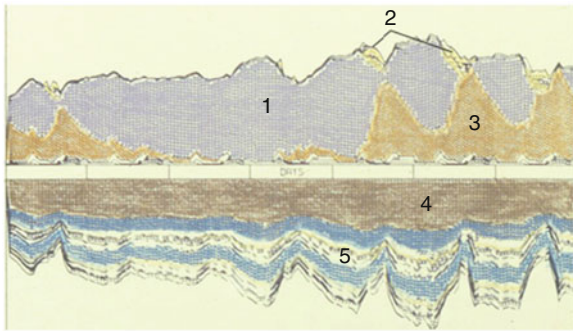
Building bioclimatic chart. The chart indicates parameters of local climatic conditions favorable for bioclimatic design strategies (Based on Givoni [3] and Arens [5])

confirmation that each climatic region has its own most appropriate design techniques. But finally, the difference between one top strategy and another was for the most part not so far ahead of others that there is any one answer. Designers have a choice, within a set of high performing strategies and techniques.

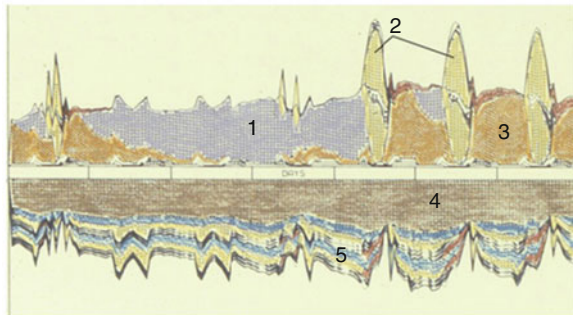
These findings are supported by a selective tabulation (Table 2), with results of the 20 city comparisons (simulated for a full year, compiling TMY data as available in 1984). For the four cities shown in Table 2, representatives of different US climates, the heating energy requirement is shown in blue and cooling in red. The “boxed” option indicates the most effective technique for combined heating and cooling energy for each location. In the case of Boston, the passive solar

and super-insulation options are approximately equal and either one represents a 40% reduction of energy required compared to the base house. The same strategies achieved more than 46% reduction in Seattle, 62% in Los Angeles, whereas none of the solar options outperformed an 18% improvement achieved simply outside insulated block walls in New Orleans. While such results are “imagined,” that is, the result of assumptions made in computation, they indicate the value of simulation to help understand the thermodynamics of climate, building design options, and resulting comfort and energy requirements.

Climatic data for computer simulation for locations worldwide are available on the Web. In regions of the world where extensive climatic data are not available



Base case house – Boston, MA



Base case w/ passive solar, insulation, shading

Bioclimatic Design. Figure 3

Simulation of bioclimatic design features. The simulation illustrates the energy performance of passive solar strategies compared to a base case in Boston, MA, climate (cool/temperate, partly sunny). (1) Heating energy required, (2) passive solar contribution, (3) thermal mass contribution, (4) roof heat loss, (5) heat loss various other surfaces (Watson and Harrington 1979. Unpublished manuscript)

and where, for example, data are limited only to monthly averages of temperature and humidity, the available data may not be coincident and must be interpreted with caution.

TMY summaries contain simultaneous climatic data for all 8,760 h in a “typical” year. Available for airport locations, mostly in the United States, each file contains one complete year of hourly data, including direct (beam) solar radiation, total horizontal solar radiation, dry-bulb temperature, dew-point humidity, wind speed, and cloud cover. Electronic files of climatic data for most US locations (major airports) are available through various sources on the Web from NREL [7]. Over 500 stations worldwide are available on the energy plus Web site [8].

Several papers by Arens [9, 10] describe techniques to interpolate multiple TMY3 data sets for locations “in between” airport locations to adjust them to match substation monthly means, or modify them further to account for the building-site surroundings.

Climate consultant is a computer-based program that can be downloaded at no cost from the Web [11]. Part of a career-long project of UCLA Professor Emeritus Murray Milne to develop public domain energy design tools [12], the software plots weather data, including temperatures, wind velocity, sky cover, percent sunshine, and beam and horizontal irradiation. It uses these data to create psychometric charts and plots hourly data in the above-mentioned zones that indicate timetables of bioclimatic needs, sun charts showing times of solar needs and shading requirements. It includes 3-D plots of temperature, wind speed, and related climatic data cross-referenced to bioclimatic design practices presented in Watson and Labs [13].

Figure 4 represents a typical bioclimatic chart generated by Climate Consultant. It displays an annual summary for Minneapolis and in the upper left, the percent (hours per year) that bioclimatic categories are effective.

Bioclimatic Design Practices

Each locale has its own bioclimatic profile, sometimes evident in indigenous and long-established building practices. Bioclimatic design techniques can be set forth as a set of design opportunities (adapted from Ref. [9]):

- *Wind breaks* (winter) – Two design techniques serve the function of minimizing winter wind exposure:
 - Use neighboring landforms, structures, or vegetation for winter wind protection.
 - Shape and orient the building shell to minimize winter wind turbulence (Fig. 5).
- *Thermal envelope* (winter) – Isolating the interior space from the hot summer and cold winter climate, such as:
 - Use attic space as buffer zone between interior and outside climate.
 - Use basement or crawl space as buffer zone between interior and grounds.
 - Use vestibule or exterior “wind-shield” at entryways.

Bioclimatic Design. Table 2 *Comparison of bioclimatic options in four US climates.* Requirements for heating (in blue) and cooling (in red) are compared for an identical “base case” house (code compliant). Different strategies are compared in representative US climates (Watson and Harrington [6])

	Base case ^a	Earth berms ^b	Trombe wall ^c	Block wall ^d	Passive solar ^e	Super insul. ^f
Boston	39.0 ^g 5.2 ^h	36.1 4.8	25.2 6.6	36.8 3.4	20.0 6.6	19 7.4
New orleans	4.4 15.9	3.9 15	.7 21.4	1.6 15.2	1.1 17.7	1.0 18.9
Los angeles	6.3 2.4	5.6 2.4	.3 3.0	1.8 2.0	.8 3.3	.7 3.6
Seattle	28.8 1.5	26.5 1.4	20.4 1.6	26.8 .5	16.4 1.7	11.5 2.3

All cases have shading and natural ventilation to reduce cooling load

^aBase case R13 walls, R20 roof, 12% glazing

^bEarthberms 4 ft. high on E, N, and W walls

^cTrombe wall 12" concrete w/R5 nightshade unvented

^dBlock wall insulated on exterior

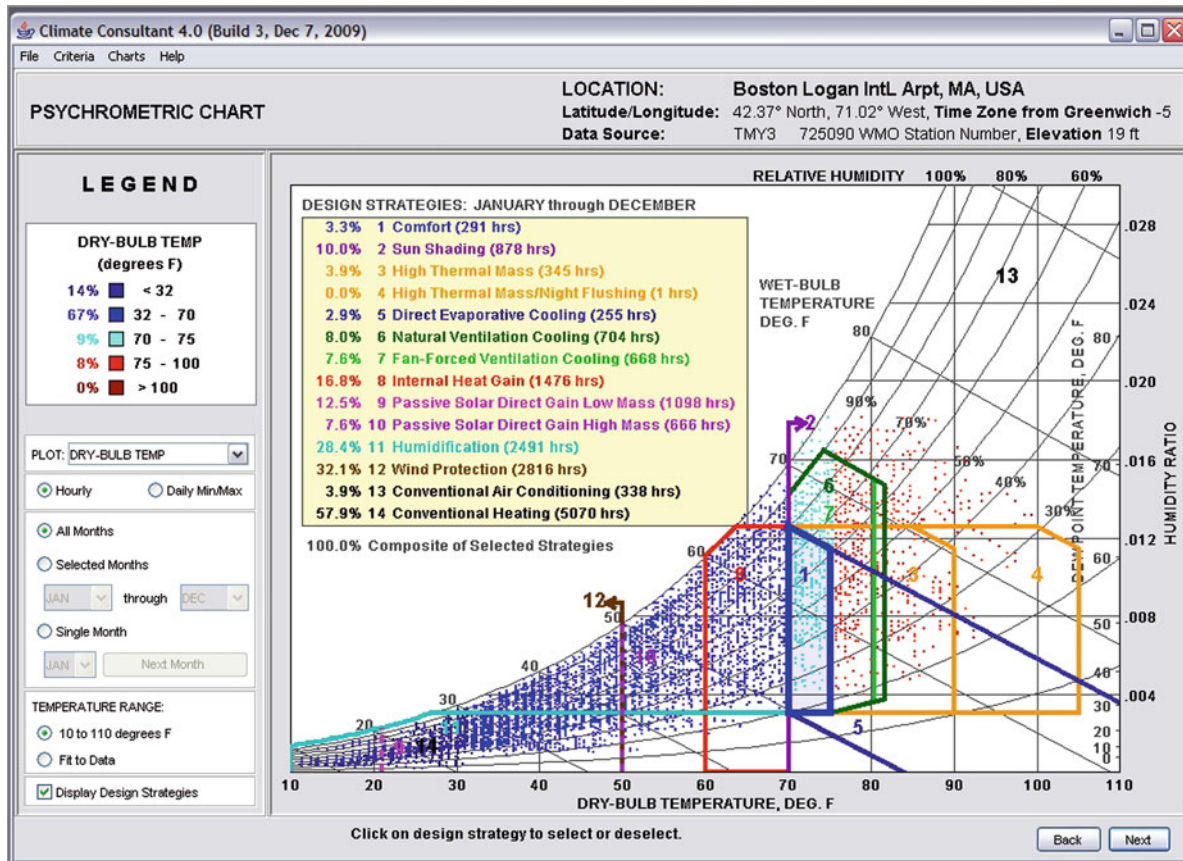
^ePassive solar R20 walls, R30 ceiling, 24% glazing, R5 nightshade

^fSuper-insulation R40 walls, R50 roof, R5 nightshade

^gHeating energy required in Btu

^hCooling energy required in Btu

- Locate low-use spaces, storage, utility, and garage areas to provide climatic buffers.
- Subdivide interior to create separate heating and cooling zones.
- Select insulating materials for resistance to heat flow through building envelope.
- Apply vapor barriers to the warm side of building envelope assemblies to control moisture migration.
- Develop construction details to minimize air infiltration and exfiltration.
- Provide insulating controls at glazing.
- Use heat-reflective (or radiant) barriers on (or below) surfaces oriented to the summer sun.
- Minimize the outside wall and roof area ratio of exterior surface to enclosed volume (Fig. 6).
- *Solar windows and walls* (winter) – Using the winter sun for heating a building through solar-oriented windows and walls is provided by a number of techniques:
 - Maximize reflectivity of ground and building surfaces outside windows facing the winter sun.
 - Shape and orient the building shell to maximize exposure to the winter sun.
 - Use high-capacitance thermal mass materials in the interior to store solar heat gain.
 - Use solar wall and roof collectors on equatorial-oriented faces.
 - Optimize the area of equatorial-facing glazing.
 - Use clerestory skylights for winter solar gain and natural illumination.
 - Provide solar-oriented interior zone for maximum solar heat gain, with solar control for shading in overheated periods (Fig. 7).
- *Indoor/outdoor rooms* (winter and summer) – Courtyards, covered patios, seasonally screened and glassed-in porches, greenhouses, atriums, and sun spaces can be located in the building plan for summer cooling and winter heating benefits:
 - Provide outdoor semi-protected areas for year-round climate moderation (Fig. 8).
- *Earth sheltering* (winter and summer) – Techniques such as banking earth against the walls of a building or covering the roof, or building a concrete floor on the ground, have a number of climatic advantages for thermal storage and damping temperature fluctuations (daily and seasonally), providing wind



Bioclimatic Design. Figure 4

Climate consultant display of the building bioclimatic chart for Albany, NY. Climate Consultant provides visual displays of the Building Bioclimatic Chart, along with a wide range of other climatic data analyses (Milne and Li [12]) Climate Consultant Web link <http://www.energy-design-tools.aud.ucla.edu/>

protection and reducing envelope heat loss or gain (winter and summer). These techniques are often referred to as earth-contact or earth-sheltering design:

- Use slab-on-grade construction for ground temperature heat exchange and thermal storage.
- Use earth-covered or sod roofs.
- Recess structure below grade or raise existing grade for earth sheltering (Fig. 9).
- *Thermally massive construction* (summer and winter) – Particularly effective in hot arid zones, or in more temperate zones with cold clear winters. Thermally massive construction provides a “thermal fly wheel.” Absorbing heat during the day from solar radiation and convection from

indoor air can create comfort if it is cooled at night, if necessary through nighttime ventilative cooling (if air temperatures fall within the comfort zone):

- Use high mass construction with outside insulation and nighttime ventilation techniques in summers.
- For selected climates (hot dry), select high-capacitance materials to dampen heat flow through the building envelope (Fig. 10).
- *Sun shading* (summer) – Because midday solar altitude angles are much higher in summer than in winter, it is possible to shade windows from the sun during the overheated summer period while allowing it to reach the window surfaces and spaces



Bioclimatic Design. Figure 5

Sea Ranch, California. Landscape planting, roof slopes, and fencing designed for wind protection. Esherick, Homsey, Dodge, and Davis, Architects and Planners with Lawrence Halprin, Landscape Architect

in winter. Providing summer sun shading does not need to conflict with winter solar heat gain:

- Minimize reflectivity of ground and building surfaces outside windows facing the summer sun.
- Use neighboring landforms, structures, or vegetation for shading the summer sun.
- Shape and orient the building shell to minimize exposure to the summer afternoon sun.
- Provide seasonally operable shading, including deciduous trees.
- *Natural ventilation* (summer and seasonal)—Natural ventilation is a simple concept by which to cool a building:
 - Shape and orient the building shell to maximize exposure to summer breezes.
 - Use an “open plan” interior to promote airflow.
 - Provide vertical airshafts to promote “thermal chimney” or stack-effect airflow.
 - Use double roof construction for ventilation within the building shell.
 - Orient door and window openings to facilitate natural ventilation from prevailing summer breezes.
 - Use wing walls, overhangs, and louvers to direct summer wind flow into the interiors.
 - Use louvered wall openings for maximum ventilation control.

- Use roof monitors for “stack-effect” ventilation (Fig. 11).

- *Plants and water* (summer) – Several techniques provide cooling by the use of plants and water near building surfaces for shading and evaporative cooling:

- Use planting next to building skin (provided it does not interfere with ventilation).
- Use roof spray or roof ponds for evaporative cooling.
- Use ground cover and planting for site cooling.
- Maximize on-site evaporative cooling (Fig. 12).

The Importance of Documenting Performance

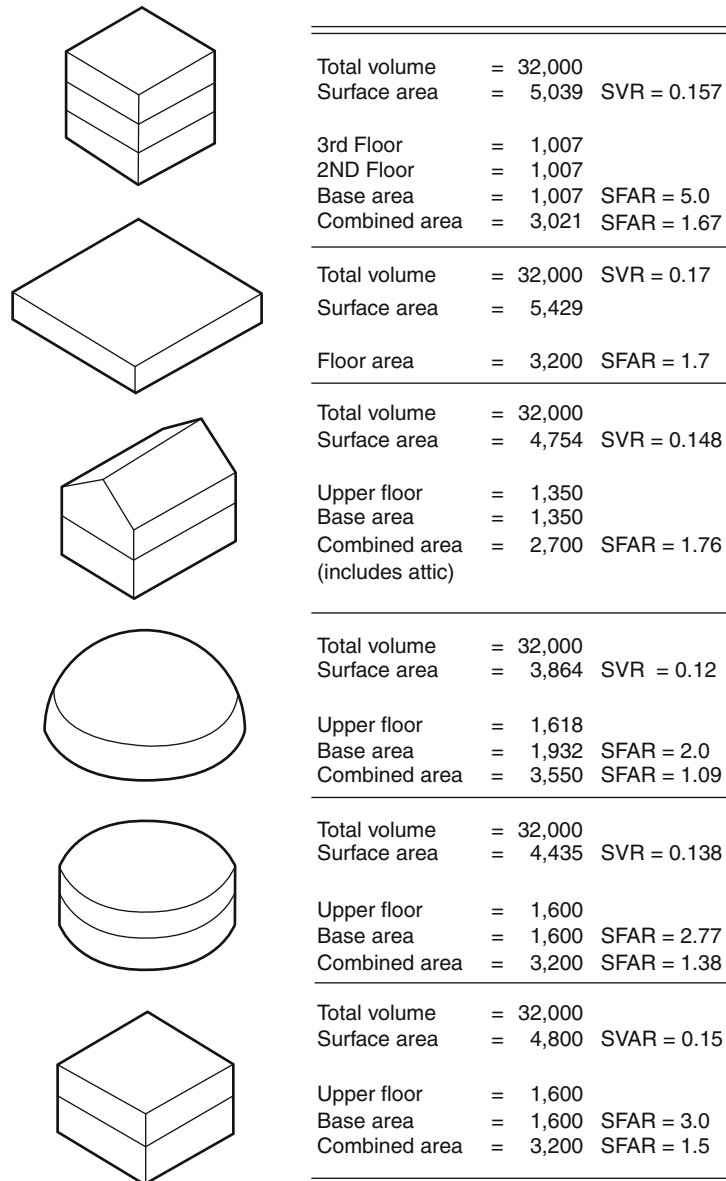
Simulation is a design tool, most appropriately used during the early design phases when alternate design techniques are considered. Simulation is not necessarily a means to predict actual performance. Design knowledge requires post-occupancy evaluation after a building is built and occupied.

To compare performance with predesign-simulated expectations requires careful monitoring of on-site weather conditions. Variations of use, user behavior, and factors as simple as how operating temperature controls are adjusted will account for greater variation than climate alone.

A post-occupancy survey was undertaken to assess 84 solar homes built with the assistance of a Solar Grant Program in Connecticut [14]. A grant of \$5,000 was offered to assist owners of existing homes to retrofit solar features, or, to incorporate into new construction. Solar features could include south-facing windows and skylights, thermal mass (Trombe wall), sunspace, and window insulation, as well as active solar domestic hot water systems. The survey asked what problems were notable after 1–5 years of occupancy, and of these what problems could be corrected and what could not (Table 3).

Bioclimatic Design of Atriums and Wintergardens

Atriums offer many energy design opportunities, depending upon climatic resources, to provide natural heating, cooling, lighting, and plants. It is necessary to establish clear design goals, defining the opportunities and liabilities of solar heating, natural cooling, and



Bioclimatic Design. Figure 6

Analysis of building aspect ratio. Simplified building shapes are compared for ratio of exterior surface to enclosed volume (Watson and Labs [13])

daylighting choices. Provisions for healthy planting and indoor gardens can be combined with atrium design, which enlarges the design criteria to include healthy conditions for plants as well as people.

The atrium concept of climate control has been used throughout the history of architecture and in indigenous building in all climates of the globe.

Suggested by its Latin meaning as “heart” or an open courtyard of a Roman house, the term “atrium” as used today is a protected courtyard or glazed winter garden placed within a building. Modern atrium design incorporates many architectural elements – wall enclosures, sun-oriented openings, shading and ventilation devices, and subtle means of modifying temperature



Bioclimatic Design. Figure 7

Solar windows walls. Keck + Keck, Architects developed solar design principles in the Chicago area in the 1930s. The solar home designs of Keck + Keck – in this example a prototype prefab homes for Green Ready-Built Homes – included large south-facing glass, exposed masonry floors with hypostyle (warm air radiant) heating, interior masonry walls, interior curtains, and exterior shading (Photo: William Keck, Architect)



Bioclimatic Design. Figure 8

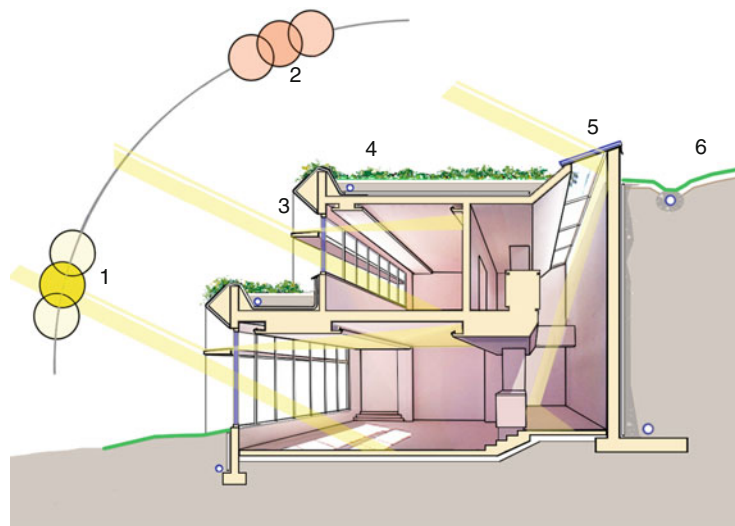
Protected courtyard. Buli Khelam Ihakhang Monastery, Bhutan. In the Himalayan tradition of building, an enclosed courtyard with sun exposed adobe walls and windows creates a wind-protected microclimate, permitting a temperate planting regime to flourish within, in contrast to high mountain climatic conditions of its locale (Photo: Donald Watson)

and humidity – suggested by examples that derive from the courtyard designs of Roman, early Christian, and Islamic buildings, and the nineteenth-century greenhouses and glass-covered arcades of Great Britain and France.

Atriums offer many energy design opportunities: first, comfort is achieved by gradual transition from outside climate to building interior; second, designed properly, protected spaces and buffer zones create natural and free-flowing energy by reducing or by



a



- 1 Winter solstice 3 Light shelf daylight reflector 5 Skylight
 2 Summer solstice 4 Green roof 6 Earthsheltering

Bioclimatic Design. Figure 9

(a) *Earth-covered home*. New Canaan CT, USA. 1986. The design combines south-facing windows with light shelves to extend daylighting and provide summer shading, skylighting, and earth sheltering (Photo: Donald Watson, FAIA, Architect). (b) *Cross-section earth-covered home*. The cross-section of the earth-covered home was designed to provide balanced daylighting throughout the year, accomplished by light shelves and a clerestory light well

eliminating the need to otherwise heat, cool, or light building interiors. Depending on climatic resources and building use, the emphasis in atrium design has to be balanced between occupancy and comfort criteria and the relative need for heating, cooling, and/or lighting.

How the atrium can work as an energy-efficient modifier of climate is best seen by examining separately its potential for natural heating, cooling, and lighting. The first step is to establish a clear set of energy design goals appropriate to the specific atrium design. The resulting solution will depend upon its program

(whether for circulation only or for longer term and sedentary human comfort and/or for plant propagation and horticultural display) and the resulting environmental control requirements.



Bioclimatic Design. Figure 10

Thermal mass appropriate for hot-dry climate. Indigenous adobe block construction, with roof and window overhangs to shade and protect the walls. Tahono O'odham Nation, Papago Indian Reservation, Arizona (Photo: Donald Watson)

Solar Heating

If heating efficiency alone is the primary energy design goal of the atrium, the following design principles should be paramount:

H1 – To maximize winter solar heat gain, orient the atrium aperture (openings and glazing) to the equator. If possible, the glazing should be vertical or sloped not lower than a tilt angle equal to the local latitude.

H2 – To store and distribute heat, place interior masonry directly in the path of the winter sun. This is most useful if the heated wall or floor surface will in turn directly radiate to building occupants.

H3 – To prevent excessive nighttime heat loss, consider an insulating system for the glazing, such as insulating curtains or high performance multilayered window systems.

H4 – To recover the heat that rises by natural convection to the top of the atrium, place a return air duct high in the space, possibly augmenting its temperature by placing it directly in the sun. Heat recovery can be accomplished if the warm air is redistributed



Bioclimatic Design. Figure 11

Shading and ventilation strategies. Built in an era well before air-conditioning, plantation manor houses such as the 1827 San Francisco Plantation House, New Orleans, combined a range of strategies for natural cooling in hot humid climates zones, including open understory and porches, cross-ventilation, and roofs designed to induce ventilation by thermal updraft (Photo: Robert Perron)



Bioclimatic Design. Figure 12

Evaporative cooling strategies: Public courtyard. Seville, Spain. The streets and passages of the city combine courtyards, gardens, and a landscape rich with planting and water fountains (Photo: Helen Kessler)

either to the lower area of the atrium (a ceiling fan) or redirected (and cleaned) to the mechanical system, or through a heat exchanger if the air must be exhausted for health and air-quality reasons.

Because a large air volume must be heated, an atrium is not an efficient solar collector per se. But the high volume helps to make an overheated space acceptable, especially if the warmest air rises to the top. If the atrium is surrounded by buildings on all sides, direct winter sun is difficult if not impossible to capture except at the top of the skylight enclosure. However, by facing a large skylight and/or window opening toward the equator, direct winter solar heating becomes entirely feasible.

In cool climates, an atrium used as a solar heat collector would require as much winter sunlight as

Bioclimatic Design. Table 3 Extract from consumer survey of 84 solar homes (Watson [14])

Perceived problems	% able to correct	% not able to correct
Glare	14	02
Excessive humidity	12	01
Condensation on windows	10	11
Keeping glass clean	26	07
Stagnant odors	10	00
Fading of furniture, walls, coverings	05	10
Lack of privacy	11	05
Drafts	07	04
Rooms cool down too fast	12	06
Not warm enough	07	02
Extreme temperature swings	10	06
Weather stripping or caulking maintenance	10	00
Covering sloped windows/skylights	05	04
Assured solar access	00	01
Zoning restriction (solar panels)	00	01
Building code restrictions (retrofit)	01	01
Mechanical/electrical failures	02	00
Overall satisfaction with program	98	02

possible. In overbright conditions, dark finishes on surfaces where the sun strikes will help reduce glare and also to store heat. On surfaces not in the direct sun, light finishes may be best to reflect light, especially welcomed under cloudy conditions. In most locations and uses, glass should be completely shaded from the summer sun. Although not practical for large atriums, in some applications greenhouse-type movable insulation might be considered to reduce nighttime heat loss.

Natural Cooling

Several guidelines related to the use of an atrium design as an intermediary or buffer zone apply to both heating and cooling. If an unconditioned atrium is located in a building interior, the heat loss is from the warmer surrounding spaces into the atrium. In buildings with large internal gains due to occupants, lighting, and machines, the atrium may require cooling throughout the year. If one were to design exclusively for cooling, the following principles would predominate:

- C1 – To minimize solar gain, provide shade for the summer sun. According to the particular building use, the local climate and the resulting balance point (the outside temperature below which heating is required); the “overheated” season when sun shading is needed may extend well into the autumn months. While fixed shading devices suffice for much of the summer period, movable shading is the only exact means by which to match the seasonal shading requirements at all times. In buildings in warm climates, sun shading may be needed throughout the year.
- C2 – To use the atrium as an exhaust air plenum in the mechanical system of the building. The great advantage is one of economy, but heat recovery options (discussed above) and ventilation become most effective when the natural airflow in the atrium is in the same direction and integrated with the mechanical system.
- C3 – To facilitate natural ventilation, create a vertical “chimney” effect by placing ventilating outlets high (preferably in the free-flow air stream well above the roof) and by providing cool “replacement air” inlets at the atrium bottom, with attention that the air stream is clean, that is, free of car exhaust or other pollutants.

The inlet air stream can be cooled naturally, such as accessed from a shaded area. In hot, dry climates, passing the inlet air over water such as an aerated fountain or landscape area is particularly effective to create evaporative cooling. Allowing the atrium to cool by ventilation at night is effective in climates where summer nighttime temperatures are lower than daytime (greater than 15°F difference), in which case the

cooling effect can be carried into the next day by materials such as masonry (although, as a rule, if the average daily temperature is above 78°F (25.5°C), thermally massive materials are disadvantageous in non-air-conditioned spaces because they do not cool as rapidly as a thermally light structure). The microclimatic dynamic is no different than that evident in the Indian tepee – when stack ventilation is possible through a roof aperture, the space will ventilate naturally even in the absence of outside breezes, by the driving force of heated air. If air-conditioning of the atrium is needed but can be restricted to the lower area of the space, it can be done reasonably; cold air, being heavier, will pool at the bottom.

While there is apparent conflict between the heating design principle to maximize solar gain and the cooling design principle to minimize it, the sun does cooperate by its change in its apparent solar position with respect to the building. There are, however, design choices to be balanced between the requirements for sun shading and those for daylighting. The ideal location for a sun shading screen is on the outside of the glazing, where it can be wind-cooled. When the outside air ranges about 80°F (26.7°C), glass areas – even if shaded – admit undesired heat gain by conduction. In truly warm climates, a minimum of glazed aperture should be used to prevent undesired heat gain, in which case the small amount of glazing should be placed where it is most effective for daylighting. Heat-absorbent or heat-reflective glass, the common solution to reduce solar heat gain, also reduces the illumination level and, if facing the equator, it also reduces desirable winter heat gain.

In temperate-to-cool climates, heat gain through a skylight can be tolerated if the space is high, so that heat builds up well above the occupancy zone and there is good ventilation. In hot climates, an atrium will perform better as an unconditioned space if it is a shaded but otherwise open courtyard.

Daylighting

In all climates, an atrium can be used for daylighting. Electric lighting cost savings can be achieved, but only if the daylighting system works, that is, if it replaces the use of artificial lighting. (Many daylit buildings end up

with the electric lights in full use regardless of lighting levels needed.) Atriums serve a particularly useful function in daylighting design for an entire building by balancing light levels – thus reducing brightness ratios – across the interior floors of a building. If, for example, an open office floor has a window wall on only one side, typically more electric lighting is required than would be required without natural lighting to reduce the brightness ratio. An atrium light court at the building interior could provide such balanced “two source” lighting. An atrium designed as a “lighting fixture” that reflects, directs, or diffuses sunlight can be one of the most pleasing means of controlling light.

The following principles apply to atrium design for daylighting:

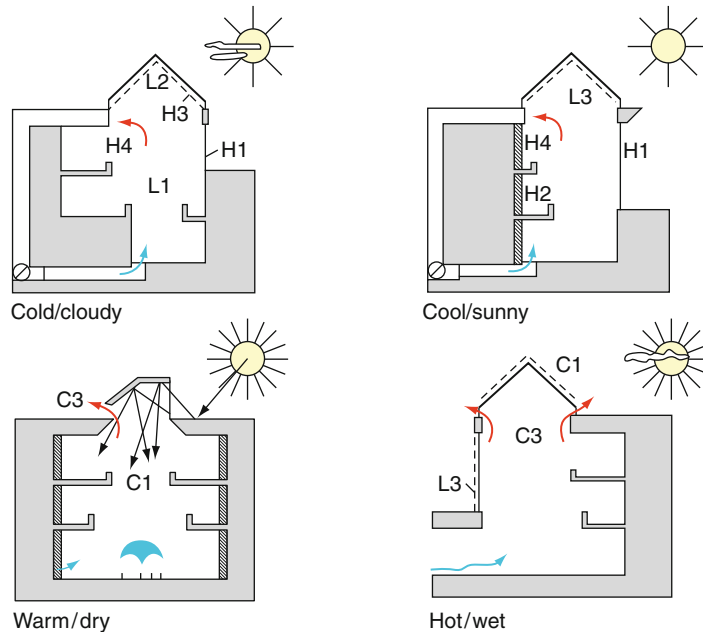
- L1* – To maximize daylight, an atrium cross-section should be stepped open to the entire sky-dome in predominantly cloudy areas. In predominantly sunny sites, atrium geometry can be based upon heating and/or cooling solar orientation principles.
- L2* – To maximize light, window or skylight apertures should be designed for the predominant sky condition. If the predominant sky condition is cloudy and maximum daylight is required (as in a northern climate winter garden), consider clear glazing oriented to the entire sky-dome, with movable sun controls for sunny conditions. If the predominant sky condition is sunny, orient the glazing according to heating and/or cooling design requirements.
- L3* – Provide sun-and-glare control by geometry of aperture, surface treatment, color, and adjustable shades or curtains. Designing for daylighting involves compromise to meet widely varying sky conditions. What works in bright sunny conditions will not be adequate for cloudy conditions. An opaque overhang or louver, for example, may create particularly somber shadowing on a cloudy day. Light is already made diffuse by a cloudy sky, falling nearly equally from all directions; the sides of the atrium thus cast gray shadows on all sides. For predominantly cloudy conditions, a clear skylight is the right choice. Bright haze will nonetheless cause intolerable glare at least to a view upward. Under sunny conditions, the same skylight is the

least satisfactory choice because of overlighting and overheating. The designer's choice is to compromise. Unless the local climate is truly cloudy and the atrium requires high levels of illumination, partial skylighting can achieve a balance of natural lighting, heating, and cooling. Partial skylighting (i.e., a skylight design that occupies only a portion of the roof surface) offers the further advantage of controlling glare and sunlight by providing reflective and shady surfaces to the view, such as by the coffers of the skylights. Because it is reduced in light intensity and contrast, a surface illuminated by reflected light is far more acceptable to the human eye than a direct view of a bright window area. Movable shades for glare and sun control provide a further means of balancing for the variety of conditions. This can be provided simply by operable canvas or fiberglass shades.

The design principles for heating, cooling, and daylighting can be applied according to building type and local climate. In the northern climates, particularly for residential units or apartments that might be grouped around an atrium, the solar heating potential predominates, while the natural cooling potential predominates in the southern United States. In commercial and institutional structures, natural cooling and daylighting are both important. In this case, the local climate would determine the relative importance of openness achieved with large and clear skylighting (most appropriate for cloudy temperate-to-cool regions) or of closed and shaded skylighting (most appropriate for sunny warm regions). While no single recommendation fits any one climate, the relative importance of each of the design principles is keyed to different climatic regions in [Fig. 13](#).

Garden Atriums

Plants have an important role in buffer zones. If the requirements of plants are understood, healthy greenery can be incorporated into atrium design and contribute to human comfort, amenity, and energy conservation. Plants, however, when uncomfortable, cannot move. Major planting losses have been reported in gardened atriums because the bioclimatic



	Cold/cloudy Seattle Chicago Minneapolis	Cool/sunny Denver St. Louis Boston	Warm/dry Los Angeles Phoenix Midland TX	Hot/wet Houston New Orleans Miami
Heating				
H1 To maximize winter solar heat gain, orient the atrium aperture to the south.	●	■	▼	
H2 For radiant heat storage and distribution, place interior masonry directly in the path of the winter sun.	▼	■	●	
H3 To prevent excessive nighttime heat loss, consider an insulating system for the glazing.	●	■		
H4 To recover heat, place a return air duct high in the space, directly in the sun	■	●	▼	
Cooling				
C1 To minimize solar gain, provide shade from the summer sun.		■	■	●
C2 Use the atrium as an air plenum in the mechanical system of the building.	■	■	■	■
C3 To facilitate natural ventilation, create a vertical "chimney" effect with high outlets and low inlets.	■	■	■	●
Lighting				
L1 To maximize daylight, use a stopped section (in predominantly cloudy areas).	■	▼		
L2 To maximize daylight, select skylight glazing for predominant sky condition (clear and horizontal in predominantly cloudy areas).	■	■	■	■
L3 Provide sun- and glare-control	■	■	●	■

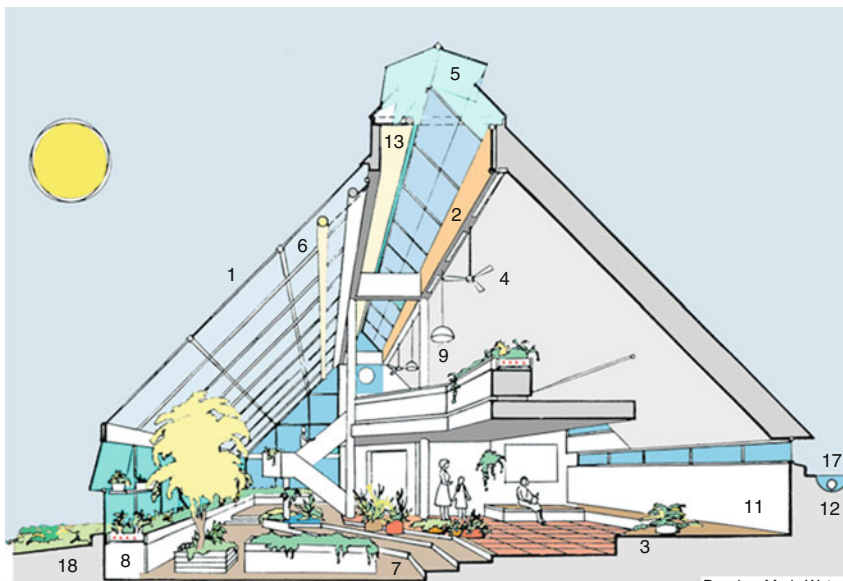
Key: ● – Very important; ■ – positive benefit; ▼ – discretionary

Bioclimatic Design. Figure 13

Appropriateness of bioclimatic principles for atrium design. The diagrams provide guidelines for the design of atria and lightcourts in various climates. Watson [15]



a



Drawing: Marja Watson

Energy design techniques

- 1 South-facing greenhouse
- 2 Solar collectors
- 3 Thermal storage elements
- 4 Ceiling fans
- 5 Roof monitor
- 6 Operable sun-shade
- 7 Earth-contact floor
- 8 Root-bed heating
- 9 Grow-lights
- 10 Composting bins
- 11 Wood stove w/ heat recovery
- 12 Well-insulated structure
- 13 Operable insulating curtain
- 14 Automatic temperature controls
- 15 Energy-efficient lighting
- 16 Water-saving plumbing
- 17 Roof-water collection
- 18 Earth-berms

Design goals

- Helps plants to grow
- Uses solar heating (winter)
- Uses natural cooling (summer)
- Uses natural lighting
- Saves non-renewable resources

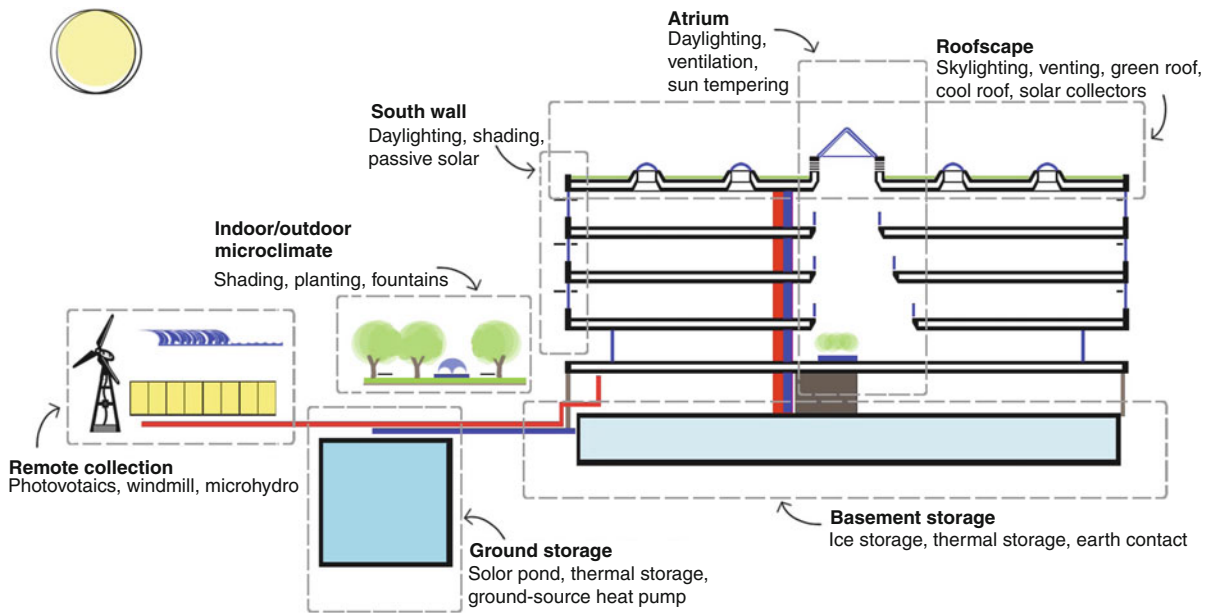
b

Bioclimatic Design. Figure 14

(a) Solar greenhouse and wintergarden. Nature Center, New Canaan, CT USA. Donald Watson, FAIA and Buchanan Associates, Architects. 1984 (Photo: Robert Perron). (b) Cross-section New Canaan Nature Center Greenhouse. A broad range of energy conserving and bioclimatic design features are integrated in the design (Illustration: Marja Watson)

requirements were not achieved. A greenhouse for year-round crop or plant production is intended to create spring-summer or the growing-period climate throughout the year. A winter garden replicates spring-

summer conditions for plant growth in wintertime by maximizing winter daylight exposure and by solar heating. Plants need ample light but not excessive heat. Although it varies according to plant species, as



Bioclimatic Design. Figure 15

Large building opportunities for microclimatic design integration. Bioclimatic design extends to a larger scale and provides lower demand for integrated heating, cooling, and lighting systems (Watson [16])

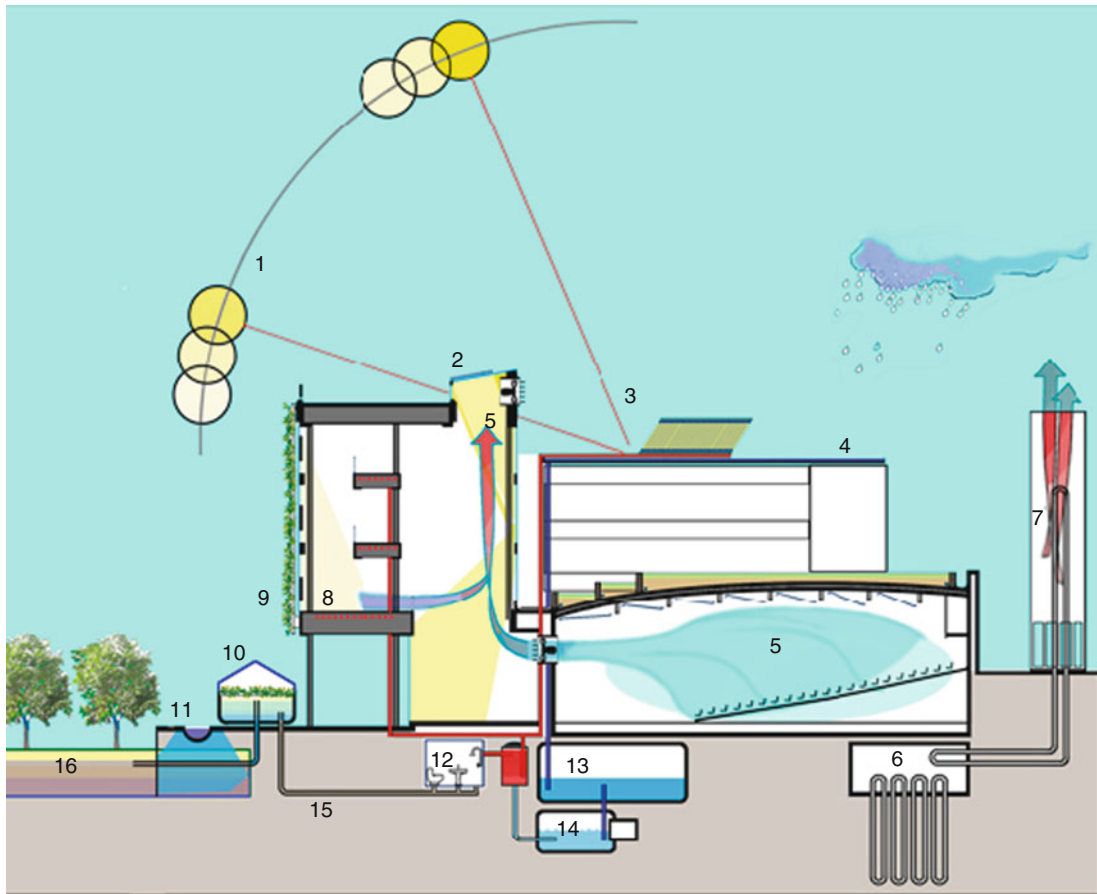
a general rule planting areas require full overhead skylighting (essentially to simulate their indigenous growing condition). Most plants are overheated if their roots range above 65°F (18.3°C). Their growth slows when the root temperature drops below 45°F (7.2°C). As a result, a greenhouse has the general problem of overheating (as well as overlighting) during any sunny day and of underlighting (in intensity and duration) during any cloudy winter day.

If the function of the atrium includes plant propagation or horticultural exhibit (replicating the indigenous climate in which the display plants flower), then clear-glass skylighting is needed for the cloudy days and adjustable shading and overheating controls are needed for sunny days. If the plant beds are heated directly, by water piping, for example, then root temperatures can be maintained in the optimum range without heating the air. As a result, the air temperature in the atrium can be cool for people, in the 50°F (10°C) range, with the resulting advantage of providing a defense against superheating the space. People can be comfortable in lower air temperatures if exposed to the radiant warmth of the sun and/or if the radiant temperature of surrounding surfaces is correspondingly higher, that

is, ranging above 80°F (26.7°C). Lower atrium temperature offers a further advantage to plants and energy-efficient space operation because evaporation from plants is slowed, saving water and energy (1,000 Btu are removed from the sensible heat of the space with each pound of water that evaporates). Air movement aids plant growth, if gentle and pervasive. Air circulation reduces excessive moisture buildup at the plant leaf and circulates CO₂, needed during the daytime growth cycle. The requirements for healthy planting and indoor gardening can thus be combined with energy-efficient atrium design for benefit of both plants and people (Fig. 14).

Large-Scale Applications

Bioclimatic design principles and practices are not limited to small-scale buildings alone. The physical basis of passive heating and cooling dynamics are somewhat constrained to near-envelope zones, subject to dimension of spaces in and around the building perimeter. However, these can and should be integrated with larger scale mechanical strategies of air movement, preheating, and ventilation.



- | | |
|-----------------------------------|---------------------------------|
| 1 Daylighting and sun tempering | 9 Deciduous living wall |
| 2 Photovoltaic collectors | 10 Solar aquatic biofiltration |
| 3 Evacuated tube solar collectors | 11 Stormwater to raingardens |
| 4 Rainwater harvesting | 12 Solar DHW |
| 5 Displacement ventilation | 13 Rainwater cistern |
| 6 Ground source heat pump | 14 Water purification |
| 7 Heat recovery | 15 Grey and blackwater recovery |
| 8 Radiant heating | 16 Greenscape irrigation |

Bioclimatic Design. Figure 16

Center for interactive research on sustainability (CIRS) University of British Columbia, Vancouver, Canada. Designed as a "living laboratory" for study of building technologies (Busby Perkins+Will, Architects)

Daylighting techniques are scalable and can be applied to exterior envelope, skylighting, and atrium (light shaft) options. The history of buildings from the nineteenth century indicates possibilities, while improved glazing, shading, and insulation increase options for natural lighting that apply to large buildings.

Figure 15 diagrams the site and building opportunities for energy collection, storage, and distribution

that may be integrated as combined passive and active means of bioclimatic design.

Several publications document 1980s' and 1990s' applications of passive solar, daylighting, and related bioclimatic elements in larger-scale buildings. Burt Hill Kosar Rittelmann/Min Kantrowitz Associates [17], provides a summary report, including several years of performance data, post-occupancy evaluation, and user surveys of 20 medium- to large-scale buildings

Passive measures	Active measures	Arctic	Tundra	Upland	Continental	Temperate	Mediterranean	Subtropical	Tropical	Savannah	Steppe	Desert
Natural ventilation					4	2	2	1	1	1	1	1
	Mechanical ventilation	3	3				4	3	2	2	2	2
Nighttime ventilation						3	2	1	1	1	1	1
	Air conditioning							3	3	3	3	2
Evaporative cooling										3	2	1
Thermal mass			4	4	2	3	2				3	2
Light construction								3	3	2	4	4
	Mechanical heating	1	1	1	1	2	4				4	
Passive solar				2	2	1	2					
Heat of occupancy		2	2	2	3	3	4					
Insulation		1	1	1	1	2	3					4
Solar control shading					4	3	2	2	2	2	1	1
	Electric lighting	2	2	4	4	4						
Daylighting		2	2	2	2	2	2	3	3	3	4	4

Key

1 Highest value

2 High value

3 Good value

4 Some value

Bioclimatic Design. Figure 17

Summary of Bioclimatic/Energy-Efficient Design Measures. The relative value of bioclimatic design strategies depends upon on climatic zone variations (Adapted from Jones cited in UNEP 2007)

assisted by the US Department of Energy Passive Solar Commercial Demonstration Grants. The grant program provided design and research assistance for building owners who had projects underway, but no so far advanced that they could not incorporate significant innovative approaches to energy conservation.

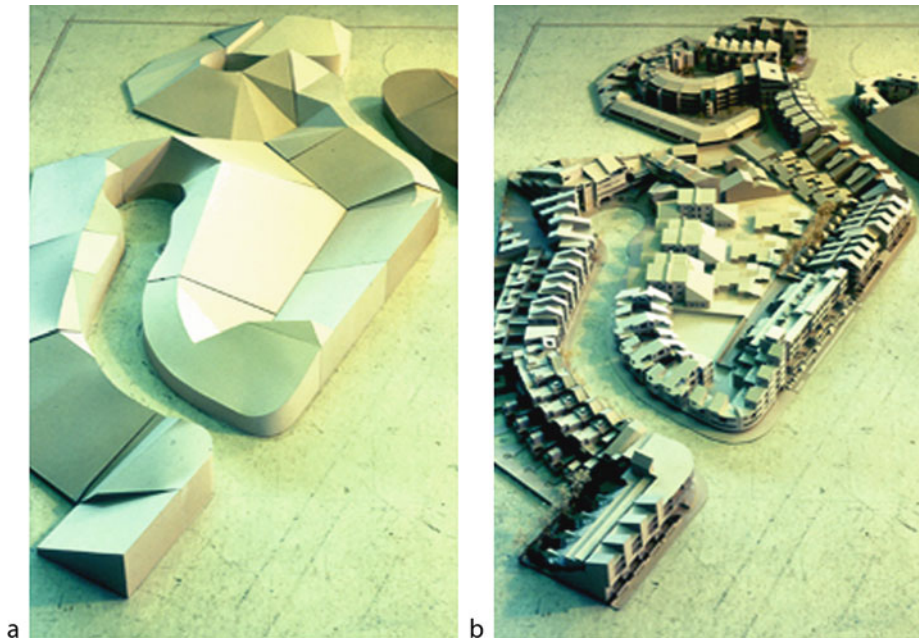
William M.C. Lam [18], provides a detailed discussion of sunlighting large buildings, including performance documentation of case studies and lessons learned. Several related projects involved faculty and students of Schools of Architecture in courses that undertake post-occupancy evaluations of completed buildings, monitoring all building energy, including air quality and daylighting, providing an archive of critical building assessments [19].

A number of current building designs at a large scale provide exemplary applications of microclimatic

design integration with heating, cooling, and lighting systems, with additional consideration of water and waste recycling. Such examples set standards for low energy and environmental impact, with relative value based upon building type and climate (Figs. 16 and 17).

Future Directions: Bioclimatic Design at the Urban Scale

Many studies address microclimatic impacts at the urban scale, described as “bioregional design” by the Olgyays [2]. Perennial topics have included solar access, evident in early twentieth-century studies related to daylighting and solar access for light and health, as well airflow and ventilation. Urban heat island effects have been addressed by studies of the effect of vegetation and “cool roofs.” The prospect of climate change and extreme weather has, in recent



Bioclimatic Design. Figure 18

(a) Solar Envelope for a medium density neighborhood of Los Angeles. (b) A possible mixed-use community conforming to the solar envelope (Photos courtesy of Ralph L. Knowles)

Bioclimatic Design. Table 4 Average air and surface temperatures measured during a sequence of several clear days in summer (Givoni [21])

Location	Air temperature (°F)	Surface temperature (°F)	Air temperature (°C)	Surface temperature (°C)
Parking lot	79	122	26.1	50.0
Open plaza	78	107	25.6	41.7
Shaded walk	76	80	24.4	26.7
Grass lawn	75	88	23.9	31.1
Behind shrubs	74	73	23.3	22.8

years, added increased concern for design for resilience, mitigation, and adaptation to extreme weather, including flooding, drought, and increasing global warming. While full discussion of these topics is well beyond the scope of this entry, a few selected references indicate foundation studies and future directions.

Solar Access

Solar geometry. Studies by Ralph Knowles [20] undertaken over several decades with students at the University of Southern California have developed the notion

of assuring solar access to buildings, for sun tempering, daylighting, and solar collection. His studies have demonstrated that solar access can be guaranteed in most urban areas while keeping within conventional medium to medium-high density floor to area ratios (FARs) (all but very high rise districts) (Fig. 18).

Bioclimatic Data at the Urban Scale

Baruch Givoni [21] compiles a broad survey of urban bioclimatic data and design applications, with emphasis on measured data, along with



Bioclimatic Design. Figure 19

Pocket Park, New York City. Paley Park creates a small area of respite, with a cooling microclimate created by evaporative cooling, shading, and wind protection, while water fountain sound helps neutralize urban clamor (Photo: Donald Watson)

discussions of challenges of data measurement at the urban scale.

Table 4 shows averages of air and surface temperatures measured at a height of 1 m (3.3 ft.) around noontime on the UCLA campus during a sequence of several clear days in summer. The lowest temperatures were in a space between a line of high shrubs and a wall of a building.

Givoni's research and overview points to opportunities for continued research at the urban scale, supporting an approach to urban planning based on bioclimatic analysis and design (Fig. 19).

Urban Air Quality

Studies of wind at the urban scale have considered force of winds for structural and exterior envelope design, as



Bioclimatic Design. Figure 20

Wind tunnel. Smoke tracing helps to visualize wind effects of building form at the urban scale (Photo: Donald Watson)

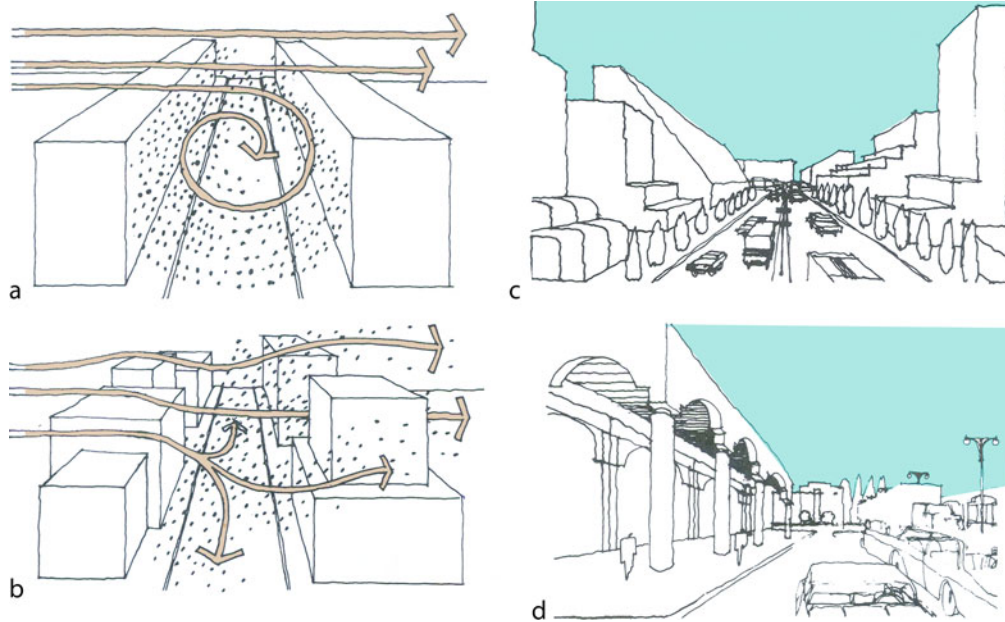
well as for wind tunnel (accelerating force of winds at constrained building openings), as well as aerodynamic shapes to induce natural ventilation. Models for such studies have included scaled wind tunnels, flow models, and full-scale mock-ups exposed to simulated wind forces (Fig. 20).

Studies by Anne Whiston Spirn [22] have utilized research on urban wind effects to propose design strategies to reduce pollution in city streets and public ways, principally by opening building forms to less constrained airflow (Figs. 21 and 22).

Resilience to Natural Disaster

Climate change is evident in global warming, extreme weather and storm events, flooding, and drought. The line of influence that climate had upon design is in a sense reversed. Design now influences climate in the way that buildings, infrastructure, cities, along with agricultural and industrial practices have in fact been executed without regard for bioclimatic impacts.

The natural landscape that has evolved in response to climate and water regimes over millennia had adapted to long-evolving patterns of rainfall, aridity, heat, and cold. Historical flood conditions were accommodated within the watershed ecology and its



Bioclimatic Design. Figure 21

Air Quality. The urban designer has opportunity to utilize strategies to improve air quality at the urban microclimatic scale. Anne WS. [22]. (a) – Street canyons lined with buildings of a similar height, oriented perpendicular to the wind direction tend to have poor air circulation compared to (b). (b) – Street canyons lined with buildings of different heights and interspersed with open areas have better air circulation. (c) – To promote air circulation in street canyons, step buildings back from the street, increase openings, and vary building heights. (d) – To promote air circulation in street side arcades, design them with high canopies and airflow outlets

coevolving plants and animals. When those patterns are disrupted and the natural landscape is altered, flooding risks and disasters increase, as much a result of human actions as natural occurrence.

While the prospect of sea level rise is undefined as to extent and time, the recent incidence of historically unprecedented natural disasters has impelled some nations and regions to undertake programs of adaptation and mitigation. The Netherlands has undertaken a 100-year plan to address flooding by an integrated and phased set of improvements to dykes, removals, and elevations of buildings in increased flood plains, and abandoning the most exposed risk area to natural recovery. In Japan, where spring flooding from mountains has resulted in flash floods in densely populated urban areas that have built up in floodplain areas, the range of actions also include “super-levees,” which essentially reconfigure land along river floodplain, while increasing floodable zones that can hold

floodwaters during peak floods, while making them available for temporary use at other times, easily evacuated in case of emergency (Fig. 23).

Watson and Adams [23], propose an extension of bioclimatic design to include design for resilience, to adopt precautionary principles in design of buildings, communities, and cities. Resiliency describes the capacity to respond to stress and change of climatic conditions. Resiliency is evident in natural systems in strategies to adjust to variable and extreme conditions. Characteristics of resilient systems include buffering, storage, redundancy, self-reliance, decentralization, diversity, energy conservation, rapid adaptability, and replacement (Table 5).

Summary

Bioclimatic design is based on the analysis of the climate, including ambient energy of sun, wind, temperature, and humidity. Bioclimatic design utilizes passive



Bioclimatic Design. Figure 22

Comprehensive plan to improve air quality. Stuttgart, Federal Republic of Germany. Public gardens and open space atop the cities hills and hillside canyons are preserved as vegetated public stairways and watercourses. The hillside canyons funnel cool nighttime airflow to center city streets and downtown parks (Photo courtesy of Dr. Michael Trieb, Urban Planning Institute, University of Stuttgart)

and ambient energy sources to achieve human comfort through building design and construction, including heating, cooling, and daylighting techniques. Derived from regional and local conditions and opportunities, bioclimatic analysis and design provide both a knowledge base and an inspiration for architecture and sustainable design.

Bioclimatic design analysis is a foundation step in architectural design, essential in the beginning phases to set design guidelines and goals, which can then be compared with actual performance results. By tracking performance results, a designer can thus gain knowledge of the effectiveness of bioclimatic design strategies and techniques for a particular locale and regional microclimates.

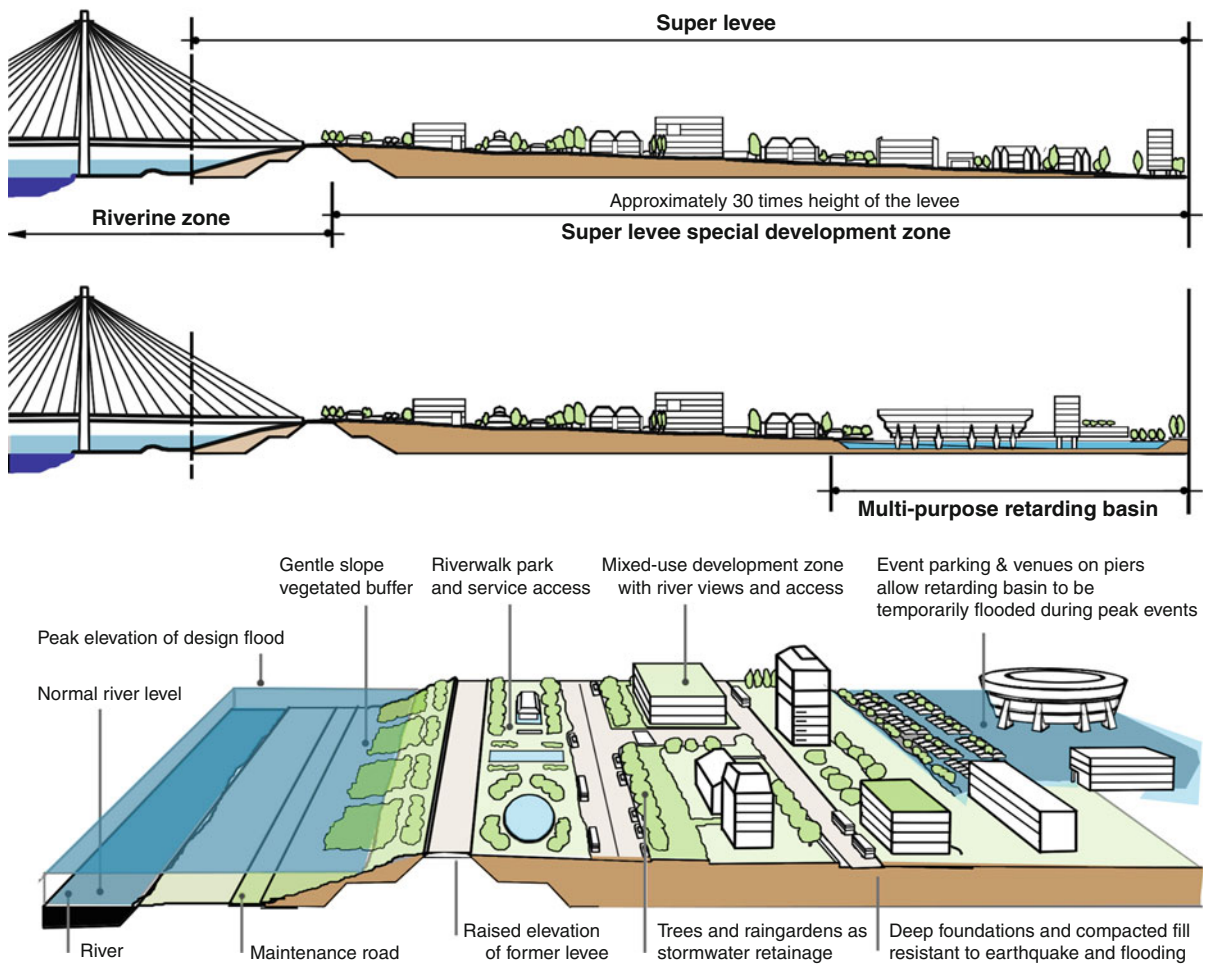
A present day challenge is climate change, which portends to increase the severity and period of warming, or overheated, conditions. Climate and weather uncertainty and warming trends should be anticipated in building design to be adaptive by a balance of techniques for heating and for cooling.

The challenge to reduce and eliminate where possible the use of fossil fuels for carbon reduction further supports the passive design strategies of bioclimatic design, for its combined advantages of comfort and health, environmental well-being, and resilience to extreme weather.

The enlargement of bioclimatic design to design for resilience is a necessary response to the increased severity of natural disaster. The science of building and urban climatology can fully inform steps to remediate flooding and other risks, so that the natural ecology of regions is returned to its role in moderating extremes and sustaining the diversity of species.

Acknowledgments

The author is indebted to Murray Milne, Baruch Givoni, and late Kenneth Labs, as well as those whose work is cited in the text and illustrations, all of whom contributed immeasurably to the development of the author's work described in this entry.



Bioclimatic Design. Figure 23

Super-levees (Japan). Designing infrastructure and buildings for resilience to flooding and extreme weather extends bioclimatic design to new needs and opportunities in regional and urban design (Watson and Adams [23])

Bioclimatic Design. Table 5 Mimicking lessons of nature for resilient design and construction

Principle from nature	Application to resilient design
Absorption	Watershed planning and design (reservoirs, retention ponds, green roofs)
Buffering	Breaks, riparian buffers, rain gardens
Core protection	Zoning, decentralization, self-reliant subsystems
Diffusion	Meanders, wetland and coastal zone landscape, open foundations
Storage capacity	Aquifers, wetlands, reservoirs, cisterns
Redundant circuits	Green infrastructure, wildlife corridors, and multiple service routes
Waste/nutrient recovery	Sustainable stormwater design and waste systems
Rapid response	Smart grid, early warning, emergency responsive systems

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Biodiesel

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Article Outline

Glossary

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Glossary

Biodiesel Fatty acid methyl or ethyl esters made out of fatty acid material.

Catalyst Chemical compound that increases the reaction rate of a chemical reaction, either soluble (homogenous) or insoluble (heterogeneous).

BtL fuels Fuels made out of biomass by gasification and further synthesis with Fischer–Tropsch catalysts.

Esterification Chemical reaction of a carboxylic acid with an alcohol forming a carboxylic ester and water.

Feedstocks Any vegetable oil, animal fat, waste oils like used cooking oil, fatty acids.

Green house gas (GHG) savings Saving of the emissions of green house gases of a biofuel in the whole production chain in comparison to fossil fuel.

Life cycle analysis Assessment of the environmental impacts of a given product caused by its production and use.

Transesterification Chemical reaction of a carboxylic ester with an alcohol or a carboxylic acid in order to obtain another carboxylic ester.

Definition of the Subject and Its Importance

The transport sector is one the fastest growing segment using fossil-based products. Especially because of the economic development in countries like India and China, there is a need for high mobility and transport. Today's transport system is based on combustion engines using fossil fuels, leading to a sharp increase of emissions of green house gases (GHG) within the last decades. Furthermore, for most of the industrialized countries there is a strong dependency on oil-producing countries, which could cause political conflicts and even wars. Therefore, especially in times of a sharp increase in crude oil prices, the question of alternative fuels or transport systems is highly discussed. Moreover, the effects of global warming caused by the increased emissions of green house gases stimulate the call for alternative fuels. For kinds of energy like electricity and heating power, there are sufficient alternatives available like photovoltaics, wind energy, and biomass; in the transport sector, the alternatives are rare. Electric vehicles could be used in special segments of the transport sector like in urban areas, but due to the limited capacity of energy storage in batteries, these electrically powered cars could not substitute combustion engines in large extent within the next decades. For aviation fuels, there has not been any suitable alternative to kerosene. The use of alternatively produced hydrogen basically could power combustion engines as well as electric cars with fuel cells, but because of the high price and lack of infrastructure there would not be a market penetration within the next decade. So the only short-term alternative for the transport sector is the use of liquid biofuels, which are produced out of biomass and could be used in existing engines. Bio-ethanol is a well-established fuel for gasoline cars, starting with activities in Brazil in the 1970s, and biodiesel made out of fats and oils is an ideal alternative fuel for diesel engines, which are the only type of engine used in heavy-duty vehicles in the transport sector but also in large extent in passenger cars in Europe. Biofuels not only can substitute to a certain extent the high demand for fuels in the transport sector

and therefore lead to less dependency on fossil fuel imports, but also have an environmental effect in lowering local emissions of soot and particles and also global emissions of green house gases. Furthermore, the production of biofuels could also contribute to social welfare by increasing the employment in the agricultural and industrial sector. However, the sustainability of biofuels production and utilization has to be proven by life cycle assessment (LCA) and thorough evaluation of the social impacts.

Introduction

The main drivers for the fast development of biofuels in the last decade worldwide where on the one side the high dependence of most of the countries on imports of fossil fuels, and on the other side the need for reduction of green house gases.

Biodiesel today is the most popular biofuel besides bioethanol. Chemically, biodiesel is defined as fatty acid methyl or ethyl esters made out of vegetable oils or animal fats. Because of the limited availability of agricultural areas and because of the food versus fuel discussion in the last years, especially, waste oils like used frying oil or animal fat as well as microbial oils from microalgae are highly favored. But also other nonfood crops like *Jatropha curcas*, which could be also cultivated on marginal areas, are currently investigated. Other biofuels for diesel engines are pure vegetable oils or biomass to liquid fuels (BtL), made via gasification of biomass and Fischer–Tropsch synthesis. As most of the biodiesel today is used as blend with fossil fuel and the warranties of most of the engine manufacturers and fuel companies only are given up to a specific amount of conventional biodiesel in fossil fuel, also hydrogenation of vegetable oils to remove the oxygen leading to hydrocarbons, which could be mixed with biodiesel also in higher amounts, is a possible route. These fuels, which are called hydrogenated vegetable oils (HVO) or NExBtL fuels, will also come into the market within the next years.

In this entry, mainly conventional biodiesel, fatty acid methyl, and ethyl ester, will be covered in detail.

History of Biodiesel

The idea to use vegetable oils as fuels for diesel engines is more than 100 years old. As Knothe points out in

a review on the historical development of biofuel production, Rudolf Diesel himself, the inventor of the diesel engine, conducted engine tests on plant oils [1]. So one prototype of his new engine presented at the World's Exhibition in Paris in 1900 ran on peanut oil and did so quite smoothly, so that hardly any visitor was aware of the fact. The idea for this test had apparently stemmed from the French government, which was searching for a means of domestic fuel production in their African colonies. Several other European countries took up the idea, which resulted in a number of articles on the use of tropical oils as diesel fuels by Belgian, French, Italian, British, and German authors. However, as petroleum-based fuels soon became available in large quantities at comparatively low cost, interest in plant oils diminished. Except for some attempts at utilizing renewable sources of energy during the Second World War, it was only in the 1970s that the worldwide oil crises and a growing environmental awareness led to the rediscovery of plant oils as possible alternatives to hydrocarbon-based fuels. The urge to fight agricultural overproduction served as an additional incentive to this development. As neat vegetable oils can only be used in modified diesel engines because of their high viscosity compared to fossil fuel, chemical transformation of the vegetable oils is the matter of choice to adapt the fuel to existing engines.

Transesterification of vegetable oils with lower alcohols has turned out to be an ideal modification, so that the term “biodiesel” is now only used to denote products obtained by this technology. The reaction between triglycerides and lower alcohols, yielding free glycerol and the fatty acid esters of the respective alcohol, was first described in 1852 [2]. The first reference to fatty acid alkyl ester fuels stems from 1937. A Belgian patent on the production of palm oil ethyl esters by acid-catalyzed transesterification describes the first use of a fuel, which would now be referred to as “biodiesel” [3]. Only a year later, in the summer of 1938, a bus fueled with palm oil ethyl esters ran between Brussels and Louvain [4]. However, these pioneering efforts in utilizing transesterified vegetable oils seem to have petered out soon afterward.

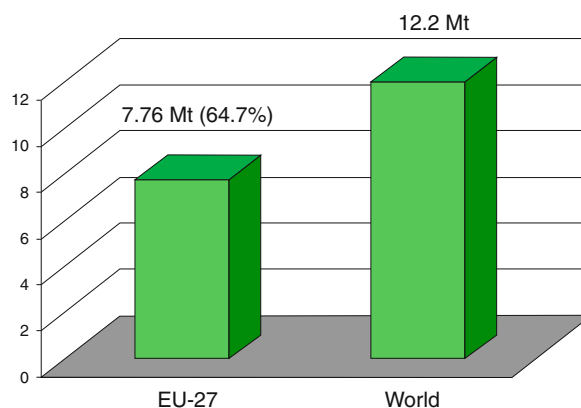
After a break in the study of fatty acid alkyl ester fuels of about 40 years, the idea was taken up again at the beginning of the 1980s. The topic was discussed in several international conferences and reappeared in

scientific publications. Rapeseed oil methyl esters (RME) was being produced and its feasibility as a diesel fuel was first being tested at Graz University [5]. Also other teams in South Africa (1981), Germany, and New Zealand (1982) soon directed their research efforts to the production of biodiesel. Already in 1987, a small pilot plant in Silberberg, Austria, started its production of rapeseed oil methyl esters, based on an innovative low-pressure, low-temperature technology, which had been developed by Mittelbach et al. 1986 [6]. The first industrial production plant for RME followed in 1991 (Aschach/Donau, Austria), and in 1995 two large-scale industrial plants in Rouen, France, and Leer, Germany, documented the rapid growth of the young biodiesel industry. The term “biodiesel” itself seems to have been coined in a Chinese article [7]. The next use of the expression in the scientific literature is documented in 1991 [8] after which the number of articles on the topic increased exponentially.

Biodiesel Production and Utilization Worldwide

Within the last decade, biodiesel production worldwide has been expanded enormously. Almost in every country worldwide, there are biodiesel activities, either in research, or in production in pilot or industrial scale. The main reasons for this rapid development are on one side the relatively easy process for transesterification of vegetable oils, which could be done without major investments, and on the other side the easy and well-established utilization of this biofuel either as pure fuel or as various blends with fossil diesel without any modifications of the engine.

As it can be seen in Fig. 1, the world production of biodiesel in 2008 was 12.2 million tons, out of which 65% have been produced in the EU-27. According to Table 1, the leading country is Germany with a long tradition in biodiesel, followed by the USA, which mostly produced biodiesel for the export to Europe; however, this export has been reduced significantly in 2009 due to new legislation in Europe. Outside Europe, the major biodiesel producers are the soybean-producing countries, namely, the USA, Argentina, and Brazil. Within Europe, there is a big gap between biodiesel production capacity and actual biodiesel production, as can be seen in Table 2. There are several reasons for that fact: First of all the dramatic increase



Biodiesel. Figure 1

Biodiesel production 2008 EU-27 and worldwide

Biodiesel. Table 1 Ranking of the biodiesel-producing countries worldwide (Source: Argentine Biofuels Chamber [9])

	Country	Biodiesel production million tons in 2008
1.	Germany	2,819
2.	USA	2,327
3.	France	1,815
4.	Brazil	1,027
5.	Argentina	960
6.	Italy	595
7.	Malaysia	420
8.	Belgium	277
9.	Poland	275
10.	Portugal	268

in vegetable oil prices in 2008, which, however, stabilized in 2009, and the insecurity on the future of biofuels as long as the new European Energy Directive had not been finalized. Furthermore, especially in Germany the introduction of mineral oil tax for pure biodiesel almost totally shut down the use of pure biodiesel (B100).

Europe is still the biggest consumer of biodiesel, about 2 million tons of biodiesel are imported. Most of the biodiesel is used in blends with fossil diesel and regularly sold at filling stations as B5 or B7, which

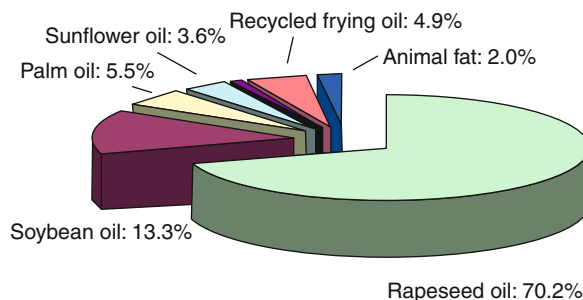
Biodiesel. Table 2 Biodiesel production and capacity in EU (European Biodiesel Board [10])

Country	Production 2008	Capacity 2009
Germany	2,819	5,200
France	1,815	2,505
Italy	595	1,910
Belgium	277	705
Poland	275	580
Portugal	268	468
Denmark/Sweden	231	352
Austria	213	707
Spain	207	3,656
UK	192	609
Slovakia	146	247
Greece	107	715
Hungary	105	186
Czech Rep.	104	325
The Netherlands	101	1,036
Finland	85	340
Others	215	1,360
Total	7,755	20,909

means 5% respectively 7%/volume blended with fossil diesel. Higher blends today have not been accepted by most of the engine manufacturers, so to reach the European goals of 10% biofuels (on an energy base) in 2020 either other biofuels have to be introduced (BtL or hydrogenated vegetable oils) or higher blends have to be used in special market segments like agriculture and captive fleets.

Feedstock for Biodiesel Production

The main feedstocks for biodiesel production are still the most common vegetable oils like rapeseed oil (Canola) or soybean oil. All major seed oils have similar fatty acid distribution, so the properties of the biodiesel produced is also quite similar except the cold temperature behavior, which depends on the sum of total saturated fatty acids. According to Fig. 2 in Europe the dominating source is rapeseed oil, which is also the main vegetable oil produced. Rapeseed oil gives



Biodiesel. Figure 2

Feedstocks for biodiesel production in Europe, estimation for 2009 (USDA [11])

a biodiesel, which meets the European specification for biodiesel, EN 14214, and has the best cold temperature behavior from all common feedstock. On the second place, there is soybean oil, which is mainly imported as biodiesel from the USA and Argentina. Biodiesel from 100% soybean oil does not meet the EN 14214 specification because of the higher Iodine Number due to the higher content of linoleic acid, however, it can be used as blend with other feedstock.

One of the most important factors for the economy of biodiesel production is the price of feedstock. Rapeseed oil is the most expensive vegetable oil for biodiesel production, so most of the biodiesel producers have to blend rapeseed oil with a certain amount of other oils, for example, used frying oil or waste animal fat. However, the amount of these products is limited and due to the high demand of these sources also the price increased significantly. One of the cheapest vegetable oil is palm oil, which is mainly produced in Malaysia and Indonesia, but the amount as blending feedstock is limited due to the poor cold temperature behavior.

The world production of vegetable oils and animal fats today is about 150 million tons, out of which already 12 million tons are used as feedstock for biodiesel. As most of the vegetable oil and animal fat production is used for food purposes, the maximum amount for biodiesel production is limited if there would not be any significant increase in oil and fat production. Twelve million tons of biodiesel together with about 40 million tons of bioethanol worldwide substitute fossil transport fuel with approximately 1.3%. As diesel fuel is the major fuel in transportation, it can be seen easily that vegetable oils and fats alone

cannot substitute diesel fuel in a significant share. So new feedstocks, which do not necessarily require common agricultural areas, have to be found in order to meet the high demand for biobased diesel fuel. High expectations were put into BtL (biomass to liquid fuels) production from lignocellulosic feedstock, so-called second-generation fuels, which however were not fulfilled until today because of high development and investment costs for such technology. Only one production plant in Freiberg, Germany (CHOREN), exists today, which until mid-2010 has not been put into standard operation. Other technologies like hydrogenated vegetable oils require the same feedstock as common biodiesel, so this route will not lead to higher amounts of biodiesel.

Promising feedstock in mid-term or long-term perspective are nonfood feedstock like *Jatropha curcas* L., which can be also grown on marginal areas or oils from microalgae that can be grown in open ponds or photobioreactors.

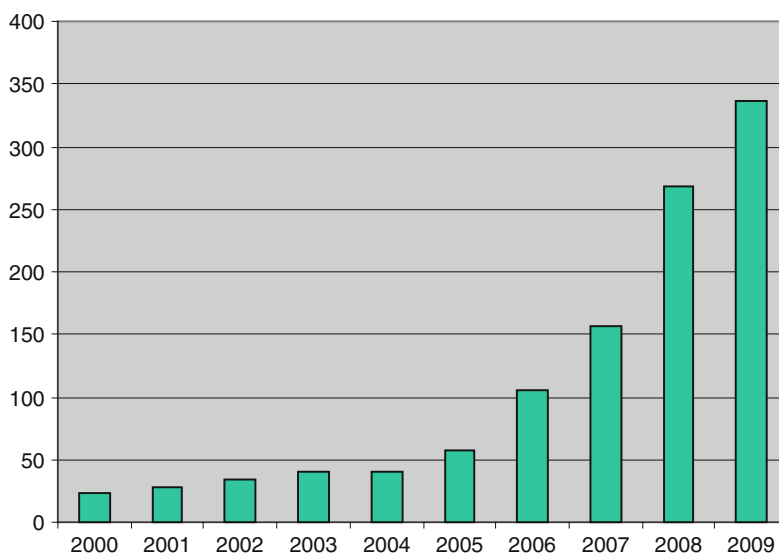
Nonedible Oils as Feedstock for Biodiesel Production

Out of the enormous potential of possible nonedible seeds, *J. curcas* as example will be described in detail to show the potential and risks of nonfood feedstock.

J. curcas has shown to be the most promising nonedible crop for biofuel production. This can be seen on the one side on the number of international *Jatropha* conferences organized during the last decade, and on the other side on the increasing number of scientific publications, which are dealing with research on *Jatropha* as alternative feedstock (Fig. 3).

The first activities in the exploration of *J. curcas* as possible feedstock for biodiesel production has been carried out within the Biomass Project in Nicaragua between 1990 and 2000, financed by the Austrian government. Within that project, a total area of 1,000 ha of *J. curcas* had been planted, and also a biodiesel plant has been installed, which however, never went into operation. One highlight of the project was the organization of the first international conference on *J. curcas* in Managua in 1997. The proceedings of that conference covered the whole spectrum of *J. curcas* knowledge at that time [13]. However, the whole project was stopped according to an external evaluation coming to the conclusion: "The biofuel part, however, suffers from the development of fossil fuel prices, which makes the production of diesel from physic nut uneconomic at the moment."

The most influencing factor for the total economic evaluation of *J. curcas* utilization is the use of the side product oil cake, which would bring the most benefit if



Biodiesel. Figure 3

Number of scientific publications on *Jatropha* according to SciFinder, CAS [12]

it could be used as animal feed. However, due to the remaining highly toxic phorbol esters in the oil cake the use as animal feed is not possible without any efficient detoxification. So today, the only possible utilization of oil cake would be the use as fertilizer, which, however, is far less profitable than the use as animal feed.

The main advantages of *J. curcas* over other food crops can be summarized in the following:

- Wide distribution in the tropics
- Good adaptation to marginal areas, poor soil
- Best adaptation to arid and semiarid conditions
- Easy agronomic handling
- No competition with food crops due to the content of toxic compounds
- High oil content in the seeds: up to 55% (dehulled)

On the other side, there are some drawbacks of *J. curcas* like the following:

- High yields need intensive agricultural production (water, fertilizer, pest control)
- Toxic seeds have to be processed in specified plants
- The use of side products like seed cake and glycerol is limited
- Harvesting is laborious, long harvesting period
- The actual yield of seeds per ha is lower than expected

One main disadvantage can be seen in the laborious harvesting, which today has to be done manually. On the one side, this fact is seen positively because the laborious harvesting could bring income to people living in rural areas, on the other side the total economy of *J. curcas* is mainly influenced by the costs of labor, which could increase rapidly. The advantage to use a nonedible crop could easily change into a disadvantage, if the utilization of side products like oil cake and glycerol is limited and less economic.

The main strategies to overcome these problems could be either the use of nontoxic varieties like some Mexican species or the detoxification of side products in order to get higher value-added products.

It can be seen that countries like China and India, where the use of food products for biofuel production is not accepted, have the greatest interest in nonedible plants like *Jatropha*. It is quite obvious that the utilization of *Jatropha* should not be focused on biofuels alone, but should include all other parts of the plants

as well as the side products of biodiesel production. Especially in China, there is a big interest in the utilization of the biologically active components in the different parts of the plant. Also the extraction of phorbol esters out of the oil and further utilization of these products is of great importance. Especially high value-added minor components and side products could improve the overall economy of *Jatropha* production and could overcome the high costs of labor-intensive manual harvesting. The use of nontoxic varieties like some species from Mexico might be challenging and attractive, however, also the possible risks have to be considered. Within a global market for seeds and oil, the coexistence between nontoxic and toxic varieties might be a high risk, especially if nontoxic oil and oil cake are considered as potential food and feed. Special certification, labeling, and control systems have to be established in order to avoid serious accidents with dramatic consequences for the whole business.

In mid-term future, the use of toxic *Jatropha* varieties will be favored, especially because of already established large investments in classical *Jatropha* plantations in a series of areas like Africa, India, Indonesia, and China. However, research in nontoxic varieties has to be carried out in order to evaluate the potential of these varieties for food and feed production. The focus for the utilization of toxic varieties will be the detoxification of the oil in order to obtain additional high value-added products, and the detoxification of the oil cake in order to get a nontoxic animal feed.

Within the last years, a significant number on reviews on *J. curcas* have been published worldwide. In two recent reviews, the latest developments in agronomy, oil production, alkyl ester production, toxicity, plant breeding, and crop expansion of *J. curcas* are discussed [14, 15]. The seeds of the plant are not only a source of biodiesel but also contain several metabolites of pharmaceutical importance. Common exploitation for biopharmaceuticals and bioenergy production are some of the prospective future potential of this plant [16, 17].

A series of publications are dealing with the detoxification of either *Jatropha* oil and/or oil cake mainly focusing on the degradation of the highly toxic phorbol esters in order to use the oil cake as

animal feed [18, 19]. However, no technically feasible method has been developed so far to totally detoxify the seed cake for safe use as an animal feed.

Potential of Microalgae as Feedstock for Biodiesel

Because of the food versus fuel discussion within the last years, microalgae as potential feedstock for biofuel production has been discussed widely around the world. High expectations have been set into this kind of biomass, because no agricultural areas are necessary for cultivation and additionally green algae need CO₂ as carbon source, which could be taken out of flue gases from power stations and could help to reduce overall green house gases.

Almost 30 years ago, the US department of energy had launched a program studying the potential of microalgae as biofuel, but the program was stopped in 1996 due to the high production costs compared to the low fossil fuel prices.

Microalgae include a variety of photosynthetic microorganisms capable of fixing CO₂ from the atmosphere to produce biomass more efficiently and rapidly than terrestrial plants; algae require approximately 2 g of CO₂ for every g biomass generated [20]. The estimated productivity lie between 10 and 50 g/m² and day, the oil content lies between 15% and 50%, so a daily overall production of 15–250 kg oil/ha could be calculated. A dry biomass yield between 73 and 350 t/ha and year is estimated, depending on a photosynthetic conversion efficiency between 2.1% and 10% [21].

However, all these data are based on the assumption, that the extracted oil mainly consists of triglycerides, which easily could be converted into well-established biodiesel. However, it has been shown, that the content of triglycerides can vary widely, and a series of non-triglyceride material like hydrocarbons and terpenes can be found in the extractable oil mixture. Furthermore, there is a series of technical questions, which have to be solved and which make the production of algae for fuels today totally uneconomic. The choice of microalgae out of thousands of different species, the cultivation method like open ponds or photo-bioreactors, the harvesting, extraction of oil, and further processing are some of the challenges that have to be faced. Today the cultivation of algae only makes sense as

integrated approach in a biorefinery, where valuable products like ω -3 fatty acids or carotenoids are produced and could be sold as nutraceuticals, proteins could be separated and used as animal feed, and the remaining biomass could be used for biofuel production.

So all in all microalgae could have a large potential for biofuel production in long-term perspectives, however, a lot of research is still necessary and the crude oil price must rise significantly in order to make the algae cultivation and processing for biofuels competitive.

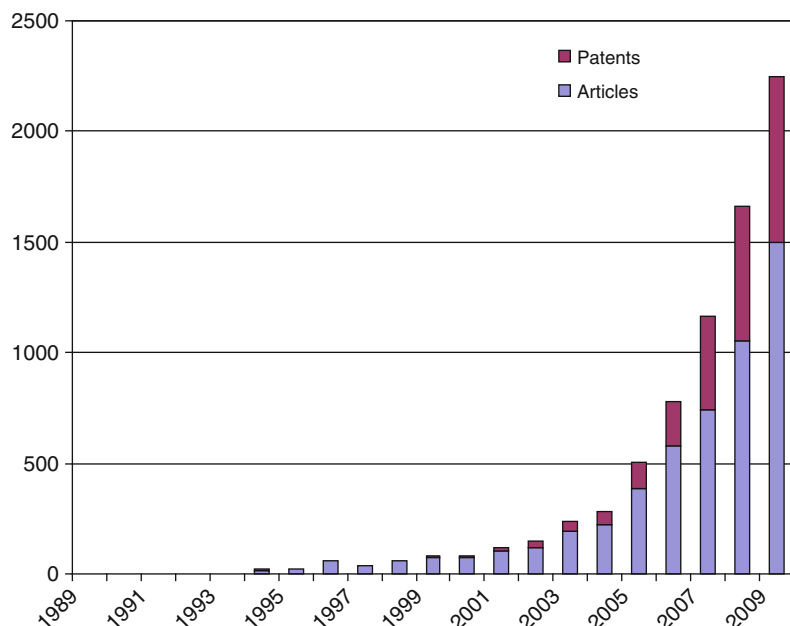
Biodiesel Production Technologies

As it can be seen in Fig. 4, the number of publications and patents dealing with biodiesel has increased enormously within the last 10 years. Especially the number of patents on biodiesel production technology per year has reached over 500. A lot of new innovations regarding new types of catalysts, new purification and refinement steps, separation techniques, and new feedstock have been developed.

Chemically, biodiesel is equivalent to fatty acid methyl esters or ethyl esters, produced out of triacylglycerols via transesterification or out of fatty acids via esterification. In Fig. 5 the formula scheme for the production of fatty acid mono alkyl esters out of triacylglycerol is shown. Fatty acid methyl esters today are the most commonly used biodiesel species, whereas fatty acid ethyl esters (FAEE) so far have been only produced in laboratory or pilot scale.

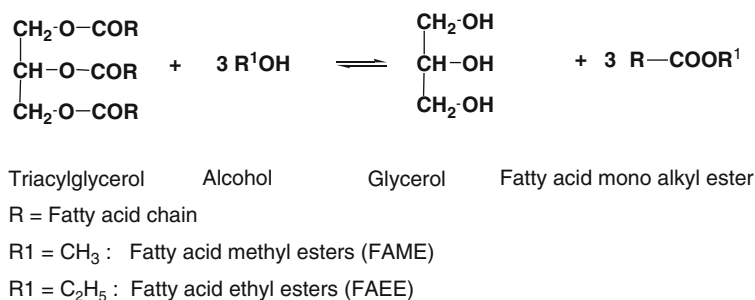
As vegetable oils or animal fats mainly consist of triacylglycerol (triglycerides) the main reaction for the production of biodiesel is the transesterification or alcoholysis reaction (Fig. 5), whereas esterification is only necessary for feedstock with higher content of free fatty acids.

In a transesterification or alcoholysis reaction, 1 mole of triglyceride reacts with 3 moles of alcohol to form 1 mole of glycerol and 3 moles of the respective fatty acid alkyl ester. The process is a sequence of three reversible reactions, in which the triglyceride molecule is converted step by step into diglyceride, monoglyceride, and glycerol. In order to shift the equilibrium to the right, methanol is added in an excess over the stoichiometric amount in most commercial biodiesel



Biodiesel. Figure 4

Number of scientific publications on "Biodiesel" according to SciFinder, CAS [12]



Biodiesel. Figure 5

Production of fatty acid mono alkyl esters via transesterification

production plants. A main advantage of methanolysis under alkaline catalysis is the fact that the two main products, glycerol and fatty acid methyl esters (FAME), are hardly miscible and thus form separate phases – an upper ester phase and a lower glycerol phase. This process removes glycerol from the reaction mixture and enables high conversion. Ester yields can even be increased – while at the same time minimizing the excess amount of methanol – by conducting methanolysis in two or three steps. Here, only

a portion of the total alcohol volume required is added in each step, and the glycerol phase produced is separated after each process stage.

Catalysts for Transesterification and Esterification Reactions

Alkaline or basic compounds are by far the most commonly used catalysts for biodiesel production. The main advantage of this kind of catalysis over acid-catalyzed transesterifications is the high conversion

rate under mild conditions in comparatively short reaction times [22]. However, free fatty acids as minor components in unrefined oils, are converted into soaps and are separated together with the glycerine phase. So the maximum conversion rate depends on the quantity of glycerides in the feedstock. For oils with higher amounts of free fatty acids, a combination of an acidic esterification of free fatty acids and an alkaline transesterification lead to a conversion of almost 100% of fatty acid material. With oils up to 3% of free fatty acid content, the combination of an alkaline transesterification and a post-esterification of the fatty acids recovered out of the glycerol phase is an optimum solution [23]. Also a pre-esterification under acidic catalysis prior to an alkaline transesterification leads to high conversion rates. Concentrated sulfuric acid can be used as cheap catalyst, but this can lead to losses due to the formation of side products, so also heterogeneous catalysts like ion exchange resins can be used [24].

As alkaline catalysts for transesterification mostly sodium or potassium hydroxide or alcoholates are used. In small- or medium-scale biodiesel production plants, the use of cheaper alkali hydroxides are preferred, however, there is the need of special equipment for dissolving the solid catalyst in methanol. As these homogeneous catalysts can only be used once, they remain as salts in the glycerol phase. For the production of raw or pharmaceutical grade glycerol, the glycerol phase has to be neutralized with an acid, and the formed alkali salts either remain in the raw glycerol or can be filtered off. If sodium hydroxide is used as catalysts, these salts are special waste and have to be disposed, whereas in the case of potassium hydroxide these salts can be reused as fertilizer. For biodiesel production in huge industrial size production plants with a capacity of 100,000 t/year or more mostly refined vegetable oils are used, which at least have to be degummed and deacidified. In this case, the use of a solution of sodium methoxide in methanol is used as catalyst. Sodium methoxide is more expensive than hydroxides, but if refined oils are used as feedstock, less catalyst can be used and the formation of soaps as side products is minimized.

Whereas traditional homogeneous catalysis offers a series of advantages, the major drawback is the fact that homogeneous catalysts cannot be reused. Moreover, catalyst residues have to be removed from the

ester product, usually with several washing steps, which increases production costs. Thus, there have been various attempts at simplifying product purification by applying heterogeneous catalysts, which can be recovered by filtration or are alternatively used as fixed-bed in continuous operation. The most frequently cited heterogeneous alkaline catalysts are alkali metal- and alkaline earth metal carbonates and oxides [25].

The main disadvantage of heterogeneous catalysis is the need for drastic reaction conditions like high temperature and pressure, which leads to higher investment costs and to higher operating compared to homogeneous catalysis. Also higher reaction temperature facilitates the formation of side products. On the other side, most of the heterogeneous catalysts can be reused for a specific time and also most of these catalysts can be used simultaneously for esterification and transesterification [26, 27]. The first technology using heterogeneous catalysts like zinc oxides or zinc aluminates is used in several commercial biodiesel production plants in France and in the USA [28, 29]. The so-called Esterfip-H process was developed by the Institut Français du Pétrole (IFP) and is designed and commercialized by Axens. The main advantages of the process are described as the production of high-quality glycerol and no need for disposal of salts resulting from the catalyst. However, the overall economic advantages have to be proved in long-term running.

Within the last years, the use of enzymes as heterogeneous catalysts for the production of biodiesel has been described widely in literature [29]. Lipases are enzymes that catalyze both the hydrolytic cleavage and the synthesis of ester bonds in glycerol esters. Their application in FAME production dates back to Choo and Ong [30], filing a patent application on lipase-catalyzed methanolysis in the presence of water, and to Mittelbach, reporting on the first water-free process for lipase-catalyzed biodiesel production [31]. As compared to other catalyst types, biocatalysts have several advantages. They enable conversion under mild temperature-, pressure-, and pH-conditions. Neither the ester product nor the glycerol phase has to be purified from basic catalyst residues or soaps. Moreover, both the transesterification of triglycerides and the esterification of free fatty acids occur in one process step. As a consequence, also highly acidic fatty materials, such as palm oil or waste oils, can be used without

pretreatment. Furthermore, enzymes could be perfectly used for the production of fatty acid ethyl esters using azeotropic technical ethanol. Though the use of enzymes seems to overcome most of the problems related to biodiesel production, the major drawback is still the price of enzymes for the production of bulk chemicals. Therefore, the enzymatic route for biodiesel production today is still too expensive for industrial application.

Basically, transesterification of triglycerides with lower alcohols also proceeds in the absence of a catalyst, provided reaction temperatures and pressures are high enough [32–34]. Above the critical temperature, a gas cannot be liquefied. The supercritical conditions show liquid as well as gaseous properties, so there have been a lot of applications for CO₂ extractions but also for carrying out chemical reactions. The advantages of not using a catalyst for transesterification are that high-purity esters and soap-free glycerol are produced. The high excess of methanol, which has to be used during supercritical transesterification, seems to make the process not economically feasible; however, a two-step process has been described, which in the first step hydrolyzes the glycerides into fatty acid with an excess of water, and in the second step esterification takes place, which requires lower amounts of methanol [35].

Though non-catalytical hydrolysis of vegetable oils today is common practice in industrial application of the production of fatty acids, the non-catalytical production of fatty acid methyl or ethyl esters has not yet been commercialized. The main reasons are the high investment costs for the high temperature and pressure procedure, and also the possibility of side reactions, which lead automatically to lower yields and higher purification costs.

A series of other approaches for biodiesel production have been reported including membrane technology for separating of methanol and glycerol from biodiesel [36], ultrasound-assisted esterification and transesterification [37], microwave-induced reactions [38], the use of different solvents for faster reaction rates [39] as well as the so-called in situ preparation of biodiesel directly from oil containing biomass have been described [40]. All these technologies seem to be very challenging and innovative, however, no practical industrial application has been reached so far mainly

due to the higher investment or running costs compared to classical technology. However, all these approaches might be interested in the future in order to improve the whole life cycle assessment of the production of biodiesel in order to meet the high demands of international legislations for sustainable production.

Biodiesel Quality and Specifications

One prerequisite for marketing an alternative fuel is the existence of specifications, which of course are based on existing specifications for mineral-based products. Biodiesel has been commercially produced since almost 20 years starting with the first industrial scale production plants in Austria and Germany in 1991. As Austria was pioneer in biodiesel production and utilization, as early as in 1991 the first national specification for biodiesel worldwide was established. This standard was based on several years of experiments with biodiesel prepared from rapeseed oil. Three years later also in Germany, national standards were established, followed by Italy and France. Because of the rapid development of biodiesel utilization in Europe there was the need for a harmonized European Specification for biodiesel. After several years of intensive negotiations and discussions in CEN committees, the harmonized European specification for biodiesel used as 100% fuel or as blend component EN 14214 came effective in 2004 [41]. In 2001, also the US standardization body ASTM published the specifications ASTM D 6751 for pure biodiesel (B100) and for blending with fossil diesel in levels up to 20% by volume [42]. The different parameters can be divided into general parameters also valid for fossil fuel and biodiesel specific parameters, which have to be added because of the different chemical composition.

In Table 4, a comparison of general and biodiesel specific parameters and limits between the latest ASTM D 6751 and EN 14214 versions is given, based on the most recent developments.

As can be seen in Table 3, the different parameters and limits between CEN and ASTM standards for biodiesel are quite similar, however there are some differences, which can be seen as barrier for international biodiesel market. Especially the limitation for Iodine Number in the European Specifications excludes

Biodiesel. Table 3 Comparison of parameters and limits in European and US specifications

Parameter	Unit	EN 14214 [2008]	ASTM D 6751 09-a
Density	15°C [kg/m ³]	860–900	–
Viscosity	40°C [mm ² /s]	3.5–5	1.9–6
Flash point	[°C]	≥101	≥93
Sulfur	[mg/kg]	≤10	≤15
Sulfated ash	[% m/m]	≤0.02	≤0.02
Conradson carbon Residue	[% m/m]	≤0.30 (10% distil. residue)	≤0.05
Cetane number	–	≥51	≥47
Water	[mg/kg]	≤500	0.05 vol%
Total contamination	[mg/kg]	≤24	–
Copper corrosion	–	Class 1	–
Oxidation stability	[h]	≥6	≥3
Acid number	[mg KOH/g]	≤0.50	≤0.50
Distillation, T90	[°C]	–	≤360
Iodine number	[g Iodine/100 g]	≤120	–
Linolenic acid	[% m/m]	≤12	–
Polyunsaturated fatty acids (>4 double bonds)	[% m/m]	≤1	–
Methanol	[% m/m]	≤0.20	≤0.20
Monoglycerides	[% m/m]	≤0.80	–
Diglycerides	[% m/m]	≤0.20	–
Triglycerides	[% m/m]	≤0.20	–
Free glycerol	[% m/m]	≤0.02	≤0.020
Total glycerol	[% m/m]	≤0.25	≤0.250
Sum of Na, K	[mg/kg]	≤5	≤5
Sum of Ca, Mg	[mg/kg]	≤5	–
Phosphorus	[mg/kg]	≤4	≤10

biodiesel made from 100% soybean oil. However, it is allowed to blend different feedstock to reach the limits. Also there are some stricter European regulations for the oxidation stability and also for the limits of phosphorus as well as for calcium and magnesium.

The European as well as the US specifications have been the basis for a series of similar specifications in many countries around the world, so all in all there are quite similar regulations worldwide. However, these limits for different parameters are only

technically based, in order to reach a sustainable biodiesel production. A lot of additional regulations have been discussed worldwide and are outlined within the next chapter.

Environmental Issues of Biodiesel

Engine Emissions

The diesel engine, also called compression ignition engine (CI), was patented by Rudolf Diesel in 1892.

Biodiesel. Table 4 Relative emissions from rapeseed oil biodiesel compared to fossil diesel (without catalytical converter) (From Mittelbach and Remschmidt, Biodiesel, the comprehensive handbook)

Reference	CO	HC	NO _x	PM
Mittelbach et al. [49]	−4%	−20%	+28%	−23%
Vellguth [50]	−8%	−20%	+7%	Soot number: −45%
Apfelbeck and Gessner [51]	−10%	−36%	+4%	−31%
Scharmer et al. [52]	±0%	−20 to −40%	−	Up to 40% lower
Krahl, Prieger et al. [53]	±0%	−10 to −20%	+10%	Up to 40% lower
Sharp [54]	−39%	−70%	+3%	−25%
May et al. [55]	−10%	−20%	+10%	−50%
Goerke [56]	−41%	−49%	+12%	−41%
Sams [57]	−16%	−33%	+4%	+11%
Krahl, Munack et al. [58]	−37%	−22%	+10%	−10%
	−39% ^a	−20%	+28%	+60%
Makareviciene and Janulis [59]	−6%	−74%	+10%	Smoke density: −68%

Unlike the spark-ignited gasoline engine, Diesel's invention works on self-ignition. Diesel engines offer a series of advantages over their gasoline-fueled counterparts. So they operate at higher compression ratios than Otto engines, which improve energy efficiency. Moreover, the fuel-to-air ratio varies with engine load and therefore with the quantity of fuel injected, resulting in lean fuel–air mixtures. This has positive effects on carbon monoxide (CO) and hydrocarbon (HC) emissions. Drawbacks of the diesel technology include a tendency for increased nitrogen oxide (NO_x) and particulate matter (PM) emissions. Moreover, diesel engines tend to be heavier than comparable gasoline engines.

With direct (DI) and indirect (IDI) injection engines, two types of combustion systems have been developed. In the first fuel is injected directly into the combustion chamber, whereas in the latter fuel is injected into a pre-chamber, from which partially oxidized gases and evaporated fuel are introduced into the main combustion chamber. Although characterized by a comparatively harsh combustion noise, DI engines are now commonly used for passenger cars due to their low fuel consumption [43, 44]. This is done at the expense of slightly increased NO_x emissions for DI engines [45].

However, modern, electronically controlled injection systems, such as the “common-rail-system,” enable a compromise between conflicting interests [46].

The major part of combustion engine exhaust streams consists of the nontoxic components nitrogen, carbon dioxide, and water. However, about 1.4% of gasoline engine exhaust and 0.2% of diesel engine exhaust are composed of more or less harmful substances. The maximum amounts of certain pollutants in exhaust gases are regulated by national authorities in various countries throughout the world. In the European Union and the USA, these limited emissions are:

- Carbon monoxide, CO
- Hydrocarbons HC, resulting from unburnt or partially burnt fuel and lubricating oil compounds. Hydrocarbons are either regulated as total hydrocarbon emissions (THC) or as non-methane hydrocarbons (NMHC).
- Nitrogen oxides NO_x, including NO, which is produced in the engine, and NO₂, which results from NO through oxidation within the exhaust stream or later in the atmosphere. Other oxides, such as N₂O, which may also be present in the exhaust gas, are not regulated. Sometimes one

combined limit for HC and NO_x is used instead of two separate limits.

- Particulate matter, which is only regulated for diesel engines.

Carbon dioxide emissions today are not limited, but due to European regulations the overall average CO₂ emissions of a fleet from a car manufacturer should not exceed 130 g/km, starting from 2012 [47].

An enormous amount of data on measurements of legally limited exhaust components all over the world is available. In comparing these results, however, some points have to be kept in mind. First, exhaust emissions differ widely according to engine types, test cycles, and fuel grades used, so that a comparison of absolute pollutant concentrations derived from different sources hardly makes sense. Instead only relative emission changes between biodiesel from rapeseed oil and fossil diesel fuels are listed in Table 4. Second, emission values are greatly influenced by the application of an exhaust gas after treatment system. To demonstrate the effects of the fuels, only data without oxidation catalytic converters are listed. As it can be seen, literature data indicate an overall slight reduction of CO and a significant reduction of HC and particulate matter emissions, whereas NO_x emissions are slightly increased. The reason for the increase of NO_x emissions with biodiesel or biodiesel blends is not yet fully understood. Especially in newer types of heavy-duty engines, the increase of NO_x emissions is rather low. An assessment of North American heavy-duty engine emission test results for biodiesel from 49 experimental studies, including both engine dynamometer and vehicle test results, shows that the use of a common biodiesel blend (B20) consistently reduces emissions of particulate matter, hydrocarbons, and carbon monoxide by 10–20%. Especially for newer types of engines, there is no statistical evidence that the average NO_x emissions increase [48].

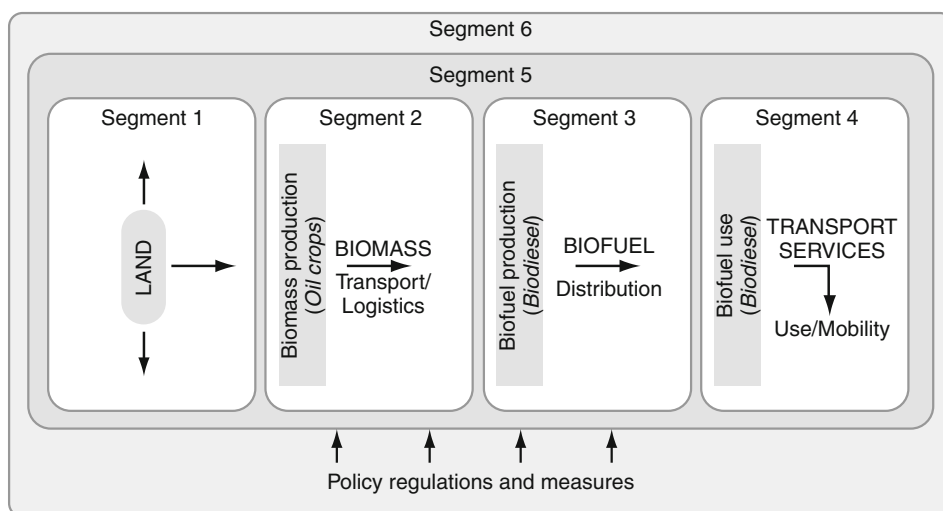
All these differences, however, will become irrelevant because of the future legislation for mandatory installation of efficient after treatment systems including particulate filters and SCR (selective catalytic reduction) technology.

Sustainability of Biodiesel

In the very first beginning of biodiesel development and utilization, no broad discussion has been taken

place on the issue, that agricultural products are used for fuel production. Especially because of rising oil prices and overproduction of agricultural products in Europe, biodiesel produced out of vegetable oils was a well-accepted alternative supported by some governments. There have been plans that biodiesel should mainly be used for agricultural production, ensuring the food supply in times of crisis. Furthermore, biodiesel production should bring a secure and continuous income for farmers, leading to a higher job rate in rural areas. However, biodiesel production was more and more industrialized, and a huge number of industrial biodiesel plants have been installed within the last 10 years around the world. The main driver was the need for the reduction of the green house gas emissions in the transport sector, leading to a number of incentives and mandates especially in Europe for the use of biofuels. The European Directive on the promotion of the use of biofuels or other renewable fuels for transport from 2003, mandating a share of biofuels in the transport sector of 5.75% until 2010 [60], led to an enormous boom of biodiesel production installations. Since 2008, however, when there has been the enormous rise in crude oil and food prices as well as in all other commodities, the fuel versus food discussion became fully effective. The consequence of this debate was the development of sustainability criteria and the assessment of the full life cycle analysis for all different biofuels. A lot of these sustainability criteria were included in the new European directive on the promotion of the use of energy from renewable sources from 2008, mandating a 10% share of biofuels in all countries of the European Union until 2020 [61].

Basically, biodiesel as renewable biofuel is considered as environmentally friendly because of saving CO₂ emissions by absorbing CO₂ during the growth of biomass [62]. However, by considering the whole life cycle of biofuels or biodiesel from production of the biomass until the final end use as fuel there are not necessarily environmental advantages. All the energy used for the whole supply chain including cultivation, the use of fertilizers and pesticides, harvesting, processing, and transport has to be considered (Fig. 6). Also the side effects of cultivation, above all the use of fertilizers producing the highly active green house gas nitrous oxide N₂O (300 times more effective



Biodiesel. Figure 6

Biodiesel supply chain (from well to wheel) [62]

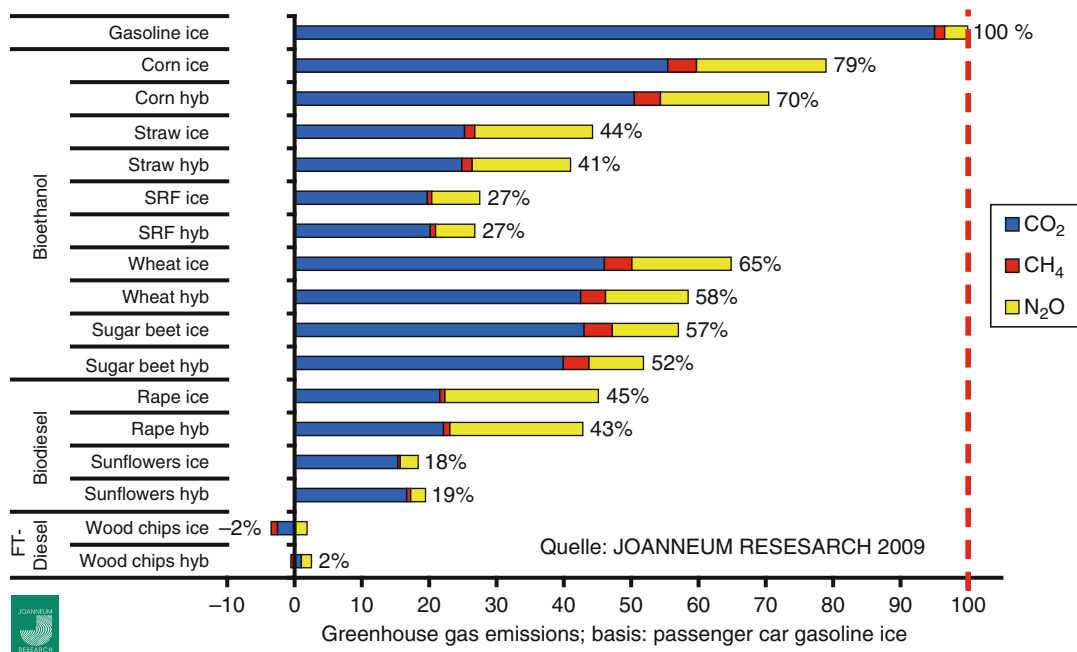
than CO₂) have to be included. Furthermore, aspects of the use of ecological sensitive areas, as well as effects of direct and indirect land use change, have to be taken into consideration. Direct land use change (DLUC) concerns the case where production of energy crops for biofuels production leads to the conversion of land actually storing carbon-like grassland into cultivated land. This could lead to an overestimation of reduction of green house gases or in the case of degraded soil it could improve the soil carbon balance. Indirect land use change (ILUC) relates to the unintended consequence of releasing more carbon emissions due to land use changes around the world induced by the expansion of croplands for biofuel production. However, in most LCA studies ILUC is not considered, because more research is needed for harmonizing and improving the methodology.

Although there is a tool for the evaluation of the life cycle assessment existing in form of an ISO standard [63], it has been applied in literature in a variety of ways and thus often leads to diverging results. LCA is often limited to energy balance or to green house gas saving balance. Several LCA studies have been carried out under various frameworks, scopes, and consistency, making it difficult to compare the results [64]. One of the most important elements is to define the system boundaries, all individual processes of the complete life

cycle have to be considered, and also all coproducts have to be taken into consideration, especially glycerol and protein as oil cake. In the so-called allocation procedure, the environmental implications of a product and its coproducts are split, whereas in the substitution procedure the desired product gets a credit, which corresponds to the environmental implications of an equivalent product [65]. The issue of allocation is one of the weaknesses of biofuels LCA.

A much simpler approach is the calculation of the energy balance, which means the ratio between the energy of biofuel produced in the engine and the total energy needed for the total production of the biofuel without considering the solar energy for the growing of the biomass. For the main feedstock rapeseed oil and soybean oil in all published data there is a positive energy balance, which means the total energy input is lower than the output. The corresponding factors for rapeseed oil lie between 1:2 and 1:3 (input:output) and for soybean oil between 1:3.2 and 1:3.5 (from *Biodiesel – The Comprehensive Handbook*). For palm biodiesel a ratio of 1:2.27–1:3.58 has been reported [66, 67].

In Fig. 7, the relative reduction of green house gas emissions of different biofuels compared to a gasoline-fueled car is outlined. It can be easily seen that the reduction varies enormously with the type of feedstock



Biodiesel. Figure 7

Reduction of GHG emissions from different biofuels in relation to fossil gasoline-fueled passenger car [68] *ice* internal combustion engine, *hyb* hybrid

and fuel. Overall a reduction of GHG emissions can be seen, the best values are obtained for biodiesel from sunflower oil and BtL Fischer–Tropsch diesel from wood chips. Bioethanol from corn and sugar beet does not show high reduction, however, bioethanol from sugar cane, which is not included in the figure, has the best values. Also biodiesel from palm oil or used frying oil or animal fat is not outlined but has a very good GHG saving potential.

According to the European Directive on the promotion of the use of energy from renewable sources [61] biofuels should reach at least 35% GHG reduction compared to fossil fuel. With effect from January 1, 2017, the greenhouse gas emission saving from the use of biofuels shall be at least 50% and from January 1, 2018, that greenhouse gas emission saving shall be at least 60% for biofuels produced in installations in which production started on or after January 1, 2017. It has to be mentioned that the data from the European Directive are based on the energy allocation method, whereas the figures presented in Fig. 7 are calculated according to the substitution method, which come closer to a real life cycle assessment.

Biofuels according to the new European Directive shall not be made from raw material obtained from land with high biodiversity value, like primary forest and other wooded land, namely forest and other wooded land of native species, highly biodiverse grassland, wetlands, and continuously forested areas.

Regarding the minimum values for GHG savings within the directive, there are typical and default values for the different biofuels produced from different sources. The default values could be used, if there are no own calculations for a specific type of biofuel, the typical values are mean values from literature data, which are always slightly higher. In Table 5, it can be seen that biodiesel from soybean oil would not meet the minimum value of 35%, so in that case it has to be proved case by case by individual calculation, that the real value are over 35%. The minimum value has to be reached by each feedstock, so blending to reach the limit is not allowed. As the minimum value will be increased up to 50% in 2017 and up to 60% in 2018 only biodiesel from waste cooking oil or animal fat will be above the limit. This would be a high risk for biodiesel from vegetable oils, if there

Biodiesel. Table 5 Typical and default values for reduction of GHG according to the European directive 2009/28/EC [61]

Biodiesel type	Typical value	Default value
Biodiesel rapeseed oil	45%	38%
Biodiesel sunflower	58%	51%
Biodiesel soybean	40%	31%
Biodiesel palm (process not specified)	36%	19%
Biodiesel palm (process with methane capture at oil mill)	62%	56%
Biodiesel waste oil/animal fat	88%	83%

would not be any significant improvement of the whole life cycle assessment. However, within the next years there will be need for further adjustments and adaptations in order to guarantee sustainable biofuel production.

Future Directions

Within the next decades, there will be a constant rising demand for biofuels due to lack of alternatives in the transport sector and the need for lowering the emissions of green house gases. Due to national and international legislation especially so-called second-generation biofuels will be favorized, which are produced from nonfood biomass like lignocellulosic material. For heavy-duty vehicles mainly used for transporting goods diesel fuel is the main energy source. One possibility to produce second-generation biodiesel is gasification of biomass and further synthesis via Fischer–Tropsch reaction (biomass to liquid, BtL). This technology however is not yet commercialized industrially because of complicated and expensive installations. So fatty acid methyl or ethyl esters produced out of fatty acid material will be still the dominant biofuel in the diesel sector in mid-term perspective. However, the kind of feedstock will be more and more focused on nonfood crops like oil from *J. curcas* or microalgae. Also the use of waste material like used cooking oil or animal fats will become more interesting. The traditional sources for production of biodiesel like rapeseed oil, soybean oil, and palm oil will still be dominant, but it is also

clear that this kind of feedstock could never substitute a significant amount of total demand of transport fuel. Theoretically microalgae, which could be grown on nonagricultural areas, could be produced in such amounts to substitute the total demand of fuels; however, a lot of research still has to be carried out in order to lower the total costs of cultivation and processing. Also all the different feedstock have to be evaluated and compared with life cycle assessments and the social impact of production and processing has to be considered carefully. So all in all biofuels will play an important role as alternative fuels in the transport sector as long as transport is based on combustion engines.

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Biodiversity in Cities, Reconnecting Humans with Nature

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Glossary

Biodiversity The variability among living organisms from all sources, including, “inter alia,” terrestrial, marine, and other aquatic ecosystems, and the ecological complexes of which they are part: This includes diversity within species, between species, and of ecosystems (United Nations – Convention on Biological Diversity).

Connectivity Landscape connectivity is the degree to which the landscape facilitates or impedes movement of plants and animals among habitat patches (cf. [70]).

Corridors and stepping stones Corridors are linear strips of habitat through the landscape of which the length, width, and design are depending on the species. Instead of continuous corridors, for some easy-migrating species (e.g., some bird species) also so-called stepping stones could support their dispersal through the city. A stepping stone connection consists of a subsequent series of small patches of habitat positioned between larger habitat structures [24, 25].

Dispersal Process of individuals leaving the place where they are resident (home) and looking for a new place to live. This behavior can occur both within and between habitat patches [33].

Fragmentation Describes the emergence of discontinuities (fragmentation) in an organism’s preferred environment (habitat), causing populations to get isolated from each other, and increased disturbance of remaining habitat. Habitat fragmentation can be caused by geological processes that slowly alter the layout of the physical environment, or by human activity such as land conversion (e.g., natural area that gets “developed” into city area), which can alter the environment much faster and causes extinctions of many species (Wikipedia).

Habitat An ecological or environmental area that is inhabited by a particular species of animal, plant, or other type of organism. For wildlife in cities, this

includes the total area used for foraging (e.g., gardens, parks), reproduction, and nesting (this may include buildings, e.g., for bats and some bird species), resting, hibernating, and migrating.

Habitat network An interconnected configuration of habitat patches and corridors.

Habitat patch A relatively homogeneous area that differs from its surroundings. Patches are the basic unit of the landscape that change and fluctuate, a process called patch dynamics. Patches have a definite shape and spatial configuration, and can be described compositionally by internal variables such as number of trees, number of tree species, height of trees, or other similar measurements [25].

Homogenization Biotic homogenization is the process by which the similarity of a biological variable increases across time and space. In the perspective of this chapter, the term “homogenization” is used to describe the increasing similarity of urban wildlife communities (especially “bird species”) in cities across the globe [44].

Landscape ecology The study of how the spatial structure of landscape elements (= different parts of the landscape) affects organism abundance at the landscape level, as well as the behavior and functioning of the landscape as a whole. This includes studying the influence of pattern, or the internal order of a landscape, on process, or the continuous operation of functions of organisms [71].

Metapopulation A metapopulation consists of a group of spatially separated populations of the same species which interact at some level. A metapopulation is generally considered to consist of several distinct populations together with areas of suitable habitat which are currently unoccupied (Wikipedia).

Urban wildlife This includes all non-domesticated animals, plants, and other organisms that live in city environments.

Definition of the Subject

Worldwide, the diversity of plant and animal life is diminishing at high speed. At the same moment, more and more humans become city dwellers, with both the proportion and absolute number of people living in cities increasing rapidly. An important link

between global biodiversity loss and fast urbanization is the enormous ecological foot print by urban dwellers, the huge demand for natural resources as required by the urban life style. Besides, a generally less well-known impact of the global urbanization of human society is the extinction of wildlife experience. People in cities lack frequent and intense human-nature interactions, as compared to our rural history. This leads to a decreased understanding of and support for plant and animal life. This not only negatively impacts biodiversity conservation efforts; it also restricts the long-term abilities of humans to benefit from nature. By promoting *urban* biodiversity, nature will be enhanced in the direct living and working environment of citizens, enabling humans to reconnect with nature.

This chapter addresses the opportunities to enhance urban biodiversity and its experience by citizens. First we illustrate how the city environment is perceived from a wildlife point of view, which is necessary to recognize opportunities to enhance urban biodiversity. Next, we discuss these opportunities one by one, illustrating with examples how to implement them in practice. We conclude with an exploration of future possibilities to integrate urban biodiversity conservation opportunities in the broader concept of sustainable city planning, design, and management.

Introduction

Why Attention for Urban biodiversity?

The latest global Living Planet Index [79] shows a decline of biodiversity about 30% between 1970 and 2007. This is based on trends in 7,953 populations of 2,544 mammal, bird, reptile, amphibian and fish species. We may therefore conclude that global biodiversity loss is currently happening on an immense scale and rate. This loss of biodiversity not only impacts ecosystem functioning, but also human well-being. The fact is that the world's ecosystems provide a wide range of services (so-called ecosystem services) that are of vital importance for the quality of human life. Degeneration of these services has huge direct or indirect negative consequences for human life: for example, (local) extinction of bees decreases pollination service and consequently food production linked to seed [2].

The urban growth of human society can be considered as one of the main causes of global biodiversity loss. According to the United Nations [73], the level of world urbanization crossed the 50% mark in 2009. In addition, between 2009 and 2050, the world population is expected to increase by 2.3 billion, passing from 6.8 billion to 9.1 billion [72]. At the same time, the population living in urban areas is projected to gain 2.9 billion, passing from 3.4 billion in 2009 to 6.3 billion 2050. Thus, the urban areas of the world are expected to absorb all the population growth expected over the next four decades while at the same time drawing in some of the rural population [73].

The impact of human lifestyle on the natural ecosystem, illustrated by a concept as the ecological footprint, is extremely high for humans living in cities [53]. As example, the city of Vancouver, Canada, requires 180 times more land to generate and process materials than the city actually occupies [52]. Already in the 1970s it was documented that modern cities consume 10–100 times more energy (per unit area) than natural systems [50]. All in all, the urban life style is an important cause of the worldwide decline of ecosystem functioning and biodiversity. It is therefore counterintuitive to think of urban areas as focal areas for biodiversity conservation, however there are several arguments to do so [45]:

1. *Source approach to diminish environmental impact:* As the majority of people is concentrated in urban areas, exploiting conservation efforts in cities (1) will reach many people and (2) any reduction in the huge city's environmental impact will be a positive step toward sustainability.
2. *To reconnect humans with nature:* Most people who live in urban areas are largely disconnected from nature. This means that a worldwide "extinction of (wildlife) experience" is currently taking place. To counteract, the places where people live and work should be designed so as to provide opportunities for meaningful interactions with the natural world. Doing so has the potential not only to engender support for protecting native species, but also to enhance human well-being [48]. Urban wildlife experience has psychological benefits for citizens [26] and may contribute to so-called socio-ecological systems, as such being an important

strategy to enhance the resilience of local citizens (see [23]).

3. *To recognize cities as (potential) biodiversity hotspots:* People, plants, and animals share the same preference for areas naturally rich of resources. Urbanization is occurring in numerous (former) biodiversity hotspots worldwide, and has been identified as a primary cause of declines in many threatened and endangered species [49]. Although urbanization processes often have diminished a large part of the original biodiversity richness, the remnant “green space” (according to its management) usually still contains a certain (potential) value for biodiversity conservation. For example, the UK city of Sheffield inhabits a high number of bird species ($n = 77$), with only three nonnative species [27].

A Different Scope: Approaching the City from a Wildlife Point of View

In natural situations, the appearance and change of landscapes and their attached biodiversity are products of abiotic and biotic processes. Human activities, such as agriculture, modify these relationships. In the urban landscape, the hierarchy of processes is absolutely different: Here, the biodiversity settlement is first depending on human appreciation and management, abiotic and biotic factors play a less important role. So, to better understand how plants and animals may survive in these man-made landscapes, a good understanding of the different actors in the urban environment and the “realities” they perceive is crucial.

Obviously, cities accommodate a range of human actors. Apart from humans as individuals inhabiting in the city (the “residents”), city dwellers employ various activities that makes that they can also be grouped as e.g., students, sportsmen, entrepreneurs, employees, patients, (allotment) gardeners, elderly people, or urban professionals (the latter term referring to those people who professionally deal with city planning, design, and management), etc. Depending on their age, societal status, and individual preferences, citizens may fit in only one or in a whole set of urban actor groups. Moreover, each of these urban actor groups, including residents, has its own favorite part of the city. They also have each their own demands

concerning what the city should deliver: Residents like nice and safe residential neighborhoods; sportsmen and - women like good and sufficient sport accommodations; etc. This makes that city planning and design can be a complex process, as there usually are many urban stakeholders to be involved.

Some of the “actors” in cities are nonhuman, being plants and animals. Most species are considered as real “wildlife” because they survive in the city on their own; others are domesticated and (partly) depend on care by humans (pets and cultivated garden plants). For all of them, cities provide them with different needs, in essence similar as for humans, being “habitats” where they can live, eat, reproduce, move, and communicate with others. However, wildlife generally has specific habitat requirements that are generally different than those of humans. For example, most birds prefer trees and shrub as nesting place above buildings (although there are exceptions as swifts and house sparrows).

To understand what the city is like as wildlife habitat, humans should project themselves in the plants and animals that inhabit city environments. This is because wildlife often evaluate the reality of the city in a different way than people would do. Three different realities of the city can be perceived by human and nonhuman urban actors:

- *Biophysical reality:* The reality of what is physically there: buildings, roads, vegetation, bare soil, open water. Geographers use to describe the physical reality (“land cover”), these days more and more supported by satellite and aerial photo images. Urban actors (both human and wildlife) perceive the biophysical reality as (one of) the realities they have to deal with.
- *Functional reality:* The reality of how the city is actually *used* by different urban actors. In their use of the city, human actors thereby take the biophysical reality (what’s there?), the functional reality (how the city is being used by themselves and others), and the planning and design reality (what is it meant to be?) in consideration. Wildlife only look to the biophysical and functional reality, the latter including the human and wildlife use. Obviously, wildlife does not take the planning and design reality into account, as they are unaware of city plans.

- *Planning and design reality*: This reality has to do with what a specific part of the city officially is designated as, or what it meant to be for. The planning reality is predominantly shaped by urban professionals in planning and design (architects, landscape architects, urban planners, regional and landscape planners etc.), and subsequently assigned in municipal, regional, federal or national plans and documents, and as such taken in consideration by human actors.

Figure 1 presents an example that illustrates the differences between the realities, and why it is important to be aware of the differences among the realities and the way they are perceived by humans and wildlife in the city.

City Environments as Wildlife Habitat

Cities as Landscape

Although most people would only associate rural and natural environments with the term “landscape”, city environments can also be considered as real

landscapes (e.g., [12]). This is because due to their size (usually $>100 \text{ km}^2$) they act on a landscape level, and because of their distinctive land use pattern they sharply contrast from their rural or natural surroundings. From a wildlife point of view the features of the urban landscape determine its habitat suitability and availability.

As the urban landscape largely consists of buildings and paved area, its stony and built-up character makes that they resemble rocky and cliff landscapes. Sky scrapers thereby act as mountain cliffs, whereas the streets between high-rise buildings (e.g., in Manhattan, New York) act as canyons. For species as the Peregrine falcon (*Falco peregrinus*), these high-rise city environments have become a secondary habitat, next to their natural cliff habitat.

Cities also appear to be different in terms of climate, as compared with the often more vegetated surrounding landscapes such as forests, swamps, mountains, or agricultural land. Because of their stone surface (and lack of the evaporation possibilities that vegetation



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 1

The Garden snail *Cornu/Helix aspersum* is a cosmopolitan species, originating from the south of Europe (Mediterranean). Buildings and surrounding green (*biophysical reality*) are considered by the snail as part of its urban habitat (*functional reality*), meanwhile humans designate these housing areas as living areas for themselves (*planning and design reality*). The coexistence of humans and these snails in residential areas leads to positive and negative interactions: the garden snail is seen as a pest for garden flowers, but also inspires people through its appearance and behavior, and acts as food for e.g., birds (which are preferred urban wildlife by residents). Photo: Robbert Snep

has), cities warm up faster, effectively retain the heat, and throw it out during the night. In addition, exhaust gases (traffic and industry) and the heating of buildings add up to an increased temperature, especially during nights. The main reason for the nighttime warming, however, is that buildings prevent surface heat from radiating into the relatively cold night sky. As a result, city night temperatures surpass the average regional temperature with several degrees. During days there is also a, yet smaller, difference in temperature. This “being warmer than the rural surroundings” phenomenon is called the UHI (*urban heat island*) effect (e.g., [69]). The UHI effect causes health problems for humans during the summer (as it contributes to extreme heat, which causes high mortality rates), but also affects wildlife in different ways. For example, in temperate climates (sub)tropical plant and animal species are more likely to survive in city environments than in the natural or rural surroundings of the city. In Northwest Europe, plant species as Common Fig (*Ficus carica*) and Olive (*Olea europaea*) from the much warmer Mediterranean region can survive in sheltered spots within cities, but would die in the rural surroundings of these cities during winters. The same process is observed on small Mediterranean ferns in France [18] showing that cities therefore present an interesting preview on how global warming may support the invasion of thermophilic species into currently colder regions.

There are more features that distinguish urban landscapes from natural and rural environments. One of them is air quality. Because of traffic and industrial gasses, the quality of city air is often worse than in the rural surroundings. The air pollution directly limits the habitat suitability of cities for e.g., most lichen species but also impacts the survival rates of urban plants and animals in general [6].

Cities are places with an excess of noise. Car traffic is a main cause of city noise, thereby making it difficult for some animal species to communicate. For example, for territorial birds it is hard to make themselves heard through the traffic noise and as such to defend their territories [54]. Recent studies have shown that bird species may adapt to the noisy city environment. Urban Coal tits (*Parus major*) sing at a higher pitch than their rural congeners, to compensate for the city background noise [61]. From other birds it is known that urban

individuals start to sing earlier in the morning than usual for these species, to avoid the noise of the city’s rush hour.

Cities are constructed in a variety of places, neglecting whether the physical conditions of the original soil may support the construction of buildings. Some cities are developed in (coastal) wetland regions or in peat soil areas, locations that are not well-equipped for construction buildings. To compensate for this, urban developers make their development sites “construction ready” by removing the original upper soil layer and adding construction-supportive sand layers. In most cities this urban development process has been happening for ages, making that urban soils are highly heterogeneous, with many different soil compositions within a small area. In addition, pedogenesis (the formation of soils) is disturbed by the actual urban land use. As large parts of the city consists of buildings and roads, these parts are sealed and thus isolated from normal interaction with rain and surface water, plant life, sun heat, etc. Also, because of the weight of buildings and heavy car traffic, the soils are compressed, decreasing their permeability for water and soil organisms. On top of this, a portion of the pollution and eutrophication coming from industry and traffic will find its way to the urban soil. As an example, urban soils often appeared to contain much higher levels of heavy metals such as lead than its rural surroundings [19]. All in all, urban soils are quite different than rural and natural soils, more contaminated and eutrophicated, as soil profiles less developed (because of a disturbed pedogenesis), spatially more heterogeneous and – with all this – thereby in general impacting the habitat quality of cities for plant and animal life in a negative way. An exception would be that, because “to be” urban development sites are usually covered with sand, these young sandy soils provide a – often temporary – habitat for plant and animal species from early successional vegetation [64]. These pioneer habitats enrich the species composition of the city’s biodiversity (Fig. 2).

The cycle of water (from clouds, precipitation, surface or groundwater back to clouds via evaporation) is essential for life on earth. On a landscape level, there are huge variations in the amount of water in each part of the cycle, as the cycle of water is taking place on a continental or even global level. In the vegetated



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 2

The Natterjack toad (*Bufo calamita*) is a pioneer species of early successional habitats, including urban fringes.

Left: tadpoles (black) of this toad species in a small temporary water body at a development location. *Right:* the male toad calling during mate season (Photo: Robbert Snep)

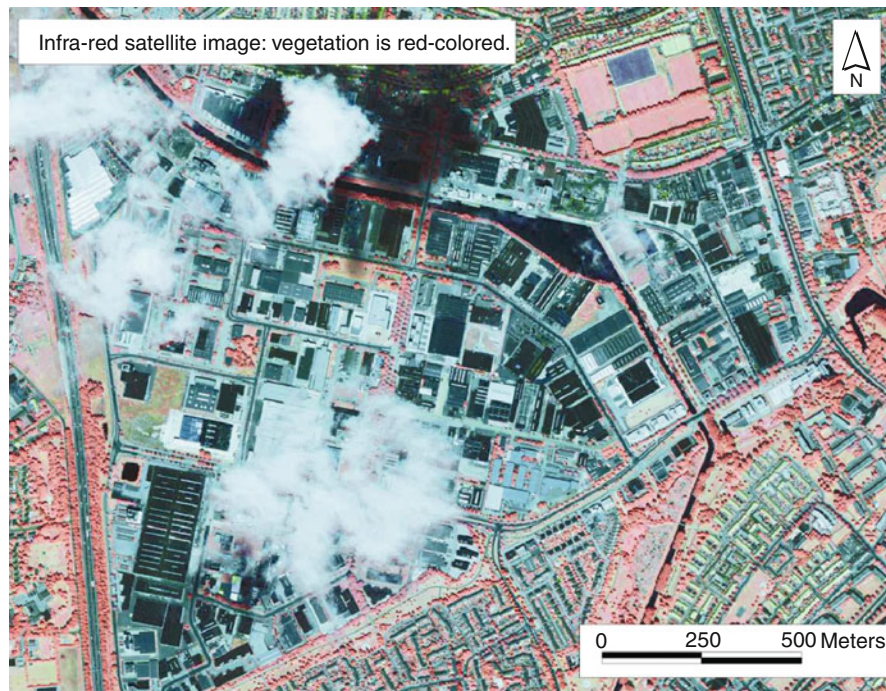
parts of the world, being the areas where most human activities occur, human land use has disturbed the water cycle process. In agricultural areas, the surface and ground water flows are highly manipulated to optimize crop yield. In urban areas, this manipulation of water has taken a much more far-reaching level. Surface water is largely canalized, with stony and steep embankments. Sewer systems catch most of the water that precipitates on buildings and streets. In cities with naturally high groundwater levels (like former wetlands), groundwater is sometimes drained or leveled in another way. The evaporation process in city areas is, due to the lack of vegetation, rather poor. In addition, urban water is contaminated by (former) industrial and household waste and by traffic, especially in cities where sewer systems do not function optimally. All in all, water is strongly manipulated in city environments. As water is a vital element for plant and animal life, the deviant quantity and quality of urban water restricts the habitat quality and availability for wildlife in cities.

Cities as Mosaic of Biotores

Although city landscapes are quite different than rural and natural landscapes, they are all but homogeneous.

City landscapes are in fact composed of a wide variety of urban land use types, ranging from residential areas, business districts, shopping malls, and (rail)road structures to urban parks, sport field complexes, allotment gardens, and cemeteries. Within each of these land use types, the actual land cover or soil occupation may also vary quite largely. The spatial heterogeneity is what makes the city that there is not such thing as “the urban biotope” (Fig. 3). Cities are mosaics of biotopes.

For long, ecologists have undervalued city environments in terms of species richness and composition. Most ecologists thought (and many of them still think) that cities would not accommodate a diversity of plant and animal life worth to study. A pioneer in the scientific field of urban ecology, Prof. Herbert Sükopp, provided the counterintuitive insight that cities are rich of species and numerous interesting ecological patterns and processes can be found here. In the 1960s, in the middle of the Cold War between the West and the Soviet Union, he was positioned at a university in West Berlin (Germany). By that time, West Berlin was governed by the West, but the surrounding area controlled by the Soviet Union. Normally, academic ecologists would leave the city and do their field work in rural and natural areas. This was not possible in the



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 3

Illustration of spatial distribution and portion of vegetation in different urban land use types: sporting fields (*right top*), residential areas (*right bottom*), infrastructure (*left*) and industrial sites (*center*). IKONOS satellite image (Photo: Robbert Snep)

case of West Berlin. Herbert Sükopp therefore decided to conduct his ecological field research within the urban area of West Berlin, a unique approach. By mapping the plant communities and biotopes of residential areas, shunting yards, and derelict industrial areas in the city in a systematic way, he discovered that urban environments have a much higher flora and plant community richness than expected. From further studies conducted in German cities, it was later also demonstrated that especially the transition zone from city to rural surroundings is species rich, and that the flora richness of cities can even be higher than the actual surrounding rural land [37]. This latter is due to two facts: (1) the heterogeneity and biotope richness of urban areas and (2) the low flora richness of the intensively managed agricultural regions in which many (German) cities are located. Modern operational management methods of farms focus on optimal yield for agricultural products, and include reshaping of the landscape (stripping off hedgerows, ponds etc.) for this purpose. Many of

the species of traditional agricultural landscapes have disappeared in the modern agricultural “deserts” due to lack of habitat; some of them find a new habitat in the small-scaled structure of the city edge. As an example, Sálek et al. [55] described a case in which the Grey Partridge (*Perdix perdix*) has colonized derelict parcels in business districts and industrial land located at the city edge.

Urban biotopes can be classified in different ways. Based upon the three realities (biophysical, functional and planning and design reality, see section “A Different Scope: Approaching the City from a Wildlife Point of View”), each classification having its pros and cons. With the *biophysical or land cover* approach, good insights in the abiotic conditions are provided, enabling ecologists where potential habitat for wildlife could be found. For this purpose aerial or satellite images supply with basic information on where vegetation and other habitat characteristics are located (using e.g., infrared sensing techniques), but additional field work is required to detail the land cover of urban



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 4

Bird monitoring in urban environments is not only conducted in backyards and urban parks, but also at industrial sites. At this photo ecologist Martin Melchers is observing urban gulls nesting at the roof of storage tanks in the Port of Amsterdam (NL) (Photo: Robbert Snep)

areas. With the *functional* approach, the actual use of the urban area by wildlife and humans is mapped. Wildlife can be monitored with a variety of techniques, of which bird counting techniques (e.g., by mapping territories) are probably most well known (Fig. 4). With these monitoring techniques, a good overview of the current habitat value of the urban area for wildlife species can be acquired. With additional inventories on the human use (recreation, traffic) of the urban area, possible causes for differences between apparently similar plots can be demonstrated. In Madrid (Spain) a study to the foraging behavior of Blackbirds (*Turdus merula*) in several urban parks showed that in parks frequently visited by people, the Blackbird behavior and density was different then in similar parks with a lower frequency of visitors [21]. Blackbirds in the more crowded parks spent more time being vigilant and moving away from people and less time searching for food (decreasing food intake). The number of pedestrians was positively correlated with Blackbird distance to pathways and negatively correlated with distance to protective cover. The number of active birds decreased with increase in the number of pedestrians during the day. Blackbird density was negatively related to the number of visitors per park. This study confirmed that human disturbance negatively affects

Blackbird feeding strategies in urban parks, ultimately modifying spatial and temporal patterns of habitat selection and abundance [21]. This study also shows that land cover and land use destination alone (in this case “urban park”) can be insufficient to determine the habitat value of urban biotopes for wildlife. The actual use of the biotope by others (humans, dogs) appears to have a – though rather invisible – impact. To implement urban ecological knowledge into the design, management, and use of the city (see “planning and design reality”), one should be able to link an urban biotope classification to the design and management jargon and concepts of the city’s public space, residential areas, business districts, etc. As there is much variety in habitat quality and quantity within each of the official urban land use types (as assigned in zoning plans), the official land use legend of the city is often not well-equipped for mapping ecological knowledge, so translation between these two different classifications can be difficult.

Fragmentation and Connectivity of (Urban) Habitat

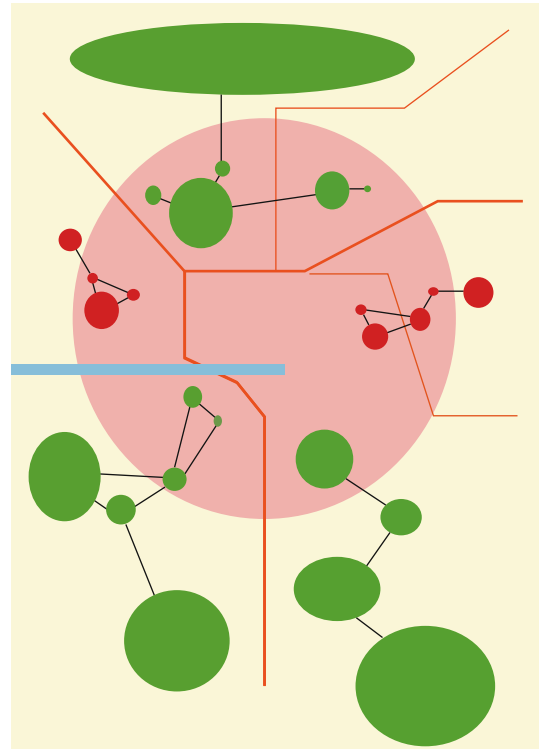
From the 1970s on, ecologists have linked the spatially explicit availability and connectivity of habitat at the landscape scale with the abundance of species at the

local scale. Ecological theories as the island biogeography [42] and the metapopulation theory [39, 51] explain how local plant and animal populations are depending of surrounding populations for their long-term persistence. The first publications about these theories mark the start of the scientific discipline of “landscape ecology.”

The island biogeography originates from comparative studies on species richness of islands and mainland, thereby illustrating that islands with a larger size and a smaller distance to the mainland are more species rich than small islands that are located far from the mainland. The size of the island thereby is a good predictor of the probability of local population extinction. The smaller the island, the generally less habitat; the smaller the island population, the higher vulnerability for a disaster to impact the whole island population, the higher the extinction rate of the island population. After local extinction, the island may be inhabited again via colonizing individuals deriving from the mainland. The distance to the mainland thereby acts as a good predictor for the colonization probability: the smaller the distance, the larger the chance that the island will be re-colonized. The island biogeography theory can also be applied in situations where there is a very large “source population” (the mainland) and smaller local populations, all located in a larger area of non-habitat.

In the past, habitat used to be much more abundant and interconnected than in current landscapes. In today’s human-dominated landscapes habitat is not only reduced in size and quality, but also fragmented by infrastructure and urban development. Here, the island biogeography with its mainland that acts as source area is not applicable, as there often is no enormous mainland habitat. The metapopulation theory is better equipped for these fragmented landscapes.

The metapopulation theory departs from the idea that in fragmented landscapes interconnected local populations may together make up a so-called metapopulation. The long-term persistence of such a metapopulation is achieved by the network setup: (1) local population extinction should be balanced with new colonization from neighboring local populations and (2) the total number of all individuals within the metapopulation should be sufficient. With an extra large local population (a so-called



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Illustration of how networks of local populations (so-called metapopulations) of a ground-dwelling species are distributed in and around a city (pink). Road (orange) and water (blue) infrastructure act as barriers and makes that there are different metapopulations (that instead of one large network). As a result, some metapopulations have sufficient size to overcome environmental fluctuations, and are viable (green), others are too small and are nonviable (red) (Photo: Robbert Snep)

key-population), this total number can be lower than in case all local populations within the metapopulation are small. As the interlinkage between local populations is crucial for the mutual exchange, the habitat pattern at landscape scale determines whether local populations will together function as a metapopulation (Fig. 5).

Several landscape parameters determine the probability that species may survive in the landscape:

- Habitat availability (the amount of habitat available for the species)
- Habitat quality (determines the carrying capacity per area of habitat)

- Habitat connectivity (extent to which habitat patches are mutually connected)
- Individual habitat patch size (determines whether there is a habitat patch in the landscape with sufficient space for a key population)
- Landscape permeability (extent to which the landscape pattern support the migration of species through the landscape, especially the size and character of the portion of nonhabitat is important in this case)
- Barriers (landscape structures that prevent the movement of species through the landscape (e.g., highways for ground-dwelling animals))

Also, some species-specific parameters determine how well the species would be equipped to survive in the landscape:

- Dispersal capacity (extent to which a species is able to migrate through the landscape, e.g., overcome barriers.)
- Dispersal distance (distance that individuals of a species are able to travel to colonize new habitat)
- Home-range size (the size of the area that an animal individual uses during everyday's activities)
- Disturbance sensitivity (level at which a species will be so much disturbed by traffic, recreation, noise, light, etc. in its habitat that this will impact its survival probability)
- Local population size (minimum amount of individuals required to function as local population)
- Key population size (minimum amount of individuals required to function as key population (and thus as an source for neighboring populations) [74])
- MVP size (minimum amount of individuals within the metapopulation necessary for a minimum viable population [59]; for metapopulations with a key population the minimum is lower than without a key population, [74]).

Each landscape is unique, each species is unique; however there are some general rules about how to deal with landscape planning and design, as seen from the viewpoint of biodiversity conservation:

1. Conserve (or re-develop) sufficient habitat area for conservation target species. "Sufficient" should meet habitat criteria for *viable* plant or animal populations [67].

2. Use the SLOSS (Single Large patch Or Several Small patches) principle while targeting (to be) habitat patches for conservation [1, 60]. This is as habitat networks should have sufficient size for a (meta) population size and sufficient connectivity (to support colonization of the patches).
3. To meet criteria for habitat connectivity, make sure that the habitat in the area is optimally interconnected, so species can migrate from one habitat patch to another [58]. In landscape and conservation planning, so-called ecological corridors are often assigned to support plant and animal dispersal [24]. These corridors are linear strips of habitat through the landscape of which the length, width, and design are depending on the species. Instead of continuous corridors, for some easy-migrating species (e.g., some bird species) also so-called stepping stones could support their dispersal through the city. A stepping stone connection consists of a subsequent series of small patches of habitat positioned between larger habitat structures.

Urban environments are highly fragmented landscapes, in which habitat availability and connectivity is generally insufficient to support the population viability norms of many species. So the application of the previous concept is not so easy. It appears today, after some urban studies on species dispersal and landscape availability to conserve populations, that complementary consideration has to be suggested in these highly fragmented urban landscapes. For example, the SLOSS rule is generally not possible and it seems interesting to promote also small green spaces and diverse kinds of green structures in dense city environments. The goal here is not to construct new large patches of biodiversity when it is not possible, but to permit, at least, both the dispersal of a maximum of species with "stepping stones" and to increase the interface between nature and citizens. After all, increasing the street plantation (street trees, road verges) in an ecological way would promote for several species the dispersal opportunities in towns: from park to park, and between areas of private gardens and business areas.

Another process that is generally forgotten is the impact of the city on the capacity of species dispersion at regional level. Under climatic change, wildlife

modifies their biogeographical area of distribution, moving to the north [32]. This adds a justification to the need of a good capacity of continuity in landscape at all the scales, including the urban areas. The town becoming megalopolis with continuous building land use acts as barriers to the species movement and especially to the dispersion to new area (to the north) for all the species that move with difficulty. Given transparency to the town, e.g., permitting the species movement is also a challenge of a sustainable city.

Urban Wildlife Species and Communities

On Eating and Being Eaten

The food resource and/or its quality are an important factor of the settlement of animal in town. The availability of grass for first consumers, insects or gastropods for first predators and small vertebrates for second predators are fundamental both to explain the presence of species in a habitat and to explain the stability of the biodiversity through the quality of the food chain. Obviously the urban areas do not present all the availability of food for each step of the food chain and some kinds of animals are favored. For example, the omnivorous and detritivorous animals, small (snails, flies...) as well as large (gulls, corvids, rats...) ones, are capable to use the rubbish dumps and all wastage from human activities. These species can become very numerous and create several problems of cohabitation (e.g., [10]). Other species take advantage of the feeding behavior of inhabitant that is important in private as well as public spaces. This typical urban source explains the success of pigeons [30] but also of some exotic species such as parakeets introduced in numerous towns [68]. However, the use of refuse is commonly reported for other species living in urbanized areas, for example, tits [14], blackbirds [57], gulls [7], or mammals such as raccoons [43] or foxes [56].

In general, urban areas appear clearly poor in food resources for specialist species. Wetlands are scarce, so water birds and aquatic fauna are also scares. The absence of old trees that permit settlement (shelter, food) of numerous insects and birds also explain the absence of several communities of animals. However, the town presents more and more vegetation and welcomes more animals today than some decades before.

Insectivorous birds seems to decrease in numerous European town in 1970s [28], but today these birds appear to be more numerous with the reduction of car pollution and pesticide use. In the same time, the recent reduction of some garbage sources in numerous countries has also limited the proliferation of some problematic animals (rats, gulls, ...).

For some generalist birds breeding in towns, a behavioral flexibility exists through diet plasticity, for example the Herring Gull [7], while for other generalists, such as the starling, it is less clear. Starlings can modify their diet composition in winter [20], but its diet variability in towns during the breeding period seems to be limited [46]. However, successful generalists compensate for feeding resource difficulties (poor quality of food, accessibility) linked to urbanization, and their behavioral flexibility allows to achieve similar breeding performances in rural and urban areas.

One of the characteristics of urban green spaces is the presence of a majority of exotic plants and trees. The consequence could be directly observed at the level of the community composition (e.g., more "coniferous" birds in town than in rural areas – [15]) as well as at the level of feeding behavior. For example, the bees give a more rich honey in town linked to the great diversity of exotic flowers. The quality of some urban food (richer, more fat) involves also some differences in individual morphology, and obesities can be observed in urban animals [35].

Wild predators are present in towns: foxes or stone martens are more common in suburbs but also sometimes in downtown [28]. Birds of prey such as falcons or sparrow hawks are today present in numerous European cities and some have adapted to the urban constraints changing their food items. The kestrel that eats small mammals in rural areas hunts particularly sparrows in towns. But the most important predator in town remains the domestic cat that eats numerous small birds (robins, house sparrows, ...), small mammals (shrew, vole, ...), and fragile lizards [22, 78].

Reproduction

In the same way than for food availability, the possibility to find nesting places explains the settlement or not of the species in the urban areas. For example, the study of breeding birds in town shows clearly the absence of

birds of open habitats, especially ground-nesting species such as larks [15], that need high grass and quiet places. Lancaster and Rees [38] found that cavity nesters were at an advantage in cities. However holes (in building or in trees) seem very dependent of the history of the building or of the park. The number of cavities in building appeared rapidly decreasing with the new architecture and the protection of all walls. In addition, linked to the hard urban disturbances, birds nest the higher possible and the installation of nest boxes (that are generally not sufficiently high) do not resolve always the problem of the lack of cavity. However, the management of parts of public parks in a more ecological way (especially increasing shrub plantation) favors the availability of the nesting places for numerous passerines. In the same time these sites become progressively more acceptable for a small fauna of soil, litter, grass, and shrub.

The reproduction success is highly variable according to the species. Urbanization profoundly affects the reproductive parameters of birds [9]. Mennechez and Clergeau [47] observed in starling that (1) although the rate at which parents feed their nestlings was higher in urban areas than in rural ones, the amount of food delivered to nestlings by parents in town was weak and (2) the body mass of nestlings reared in the urban sector was significantly lower. This supports the idea that urban nestlings received insufficient food loads or food of low quality (refuse food). Urban environment imposes severe constraints in terms of nutritional “conditions.” So some generalist birds such as starling can have bad reproduction in town when generalist species such as the kestrel can have good urban breeding performance [36]. It seems difficult to generalize a relationship between habitat generalist and specialist, without integrating the capacity of adaptation of the different species.

Territorial Behavior

The behavior of wildlife in town is not well studied and today only some mammals have been seriously analyzed. For example, it is well known that cats change their social organization and their territorial behavior in town. In natural and in rural areas, wild cats or

domestic cats each have a stable home range with only some spatial overlaps; the organization avoids all possibility of temporal contact. In town, the social organization is absolutely changed: Cats leave in group with one or two dominant males. The impact of punctual and abundant source of food (by human feeders) explains this structure [40].

The fox has been well studied and comparison between rural and urban are conducted in several countries (e.g., [31]). All the studies give the same results: The territory of urban foxes is smaller in town and changes regularly of place. The higher mobility of urban foxes is linked to the high mortality that involves change of individual and permanent reorganization of territories, but also to the shelter availability. In town the majority of fox holes do not exist and animals sleep during the day just in flower clumps, within pipeline, under bridge, etc.

Alien and Invasive Species

Numerous exotic animals and plants have settled into new geographical regions after voluntary or involuntary releases by humans. Although only 1% of alien plants have established populations and spread (Williamson 1996), this percentage can reach 15–50% for vertebrates [34]. When these alien populations increase in number, they often exert negative pressures on the native ecosystem, especially in terms of predation or competition with native species [75]. However, in numerous cases, the mechanisms underlying their success and the potential impacts of these aliens are not sufficiently well documented. The urban areas are the first source of introduced species [16] for plants with horticulture and garden plantation, and for animals with trade of pets. This process becomes an important point of biodiversity management also in town with the goal of urban corridors permitting the dispersion from and to the town (see after).

Consequently, a change in the work of landscape gardeners is awaited in order to limit the use of exotic species known as invasive in new garden and park management. This is especially important for site adjacent to rural and natural zones.

For animals too, the trade need to be examined but also the behavior of citizen that releases all kind of

exotic pets. One recurrent human behavior that seems to facilitate the establishment of exotic species in temperate regions and often in town is the supplemental provisioning of food. The provisioning behavior is observed for numerous exotic mammals (e.g., Coypu *Myocastor coypus*, Siberian chipmunk *Tamias Sibericus*, Grey squirrel *Sciurus carolinensis*), and birds (e.g., Mute swan *Cygnus olor*, Rock dove *Columba livia*, Rose-ringed Parakeet *Psittacula krameri*) and it could be one of the keys to the success of these species. Limiting the supplemental feeding of alien species could be an element of management for some invasive species and needs to be evaluated [13].

Urban Survival Strategies

Blair [4] working on birds and butterflies defined different kind of species according to their ability to colonize and settle in the town. He recognizes species that avoid the urban areas (the “avoiders” that are never present in this habitat) from species that exploit the town (the “exploiters”). These exploiters are generally “adapters” that modify their behavior to exploit better the town. Urban environment seems to impose so many constraints on birds (e.g., landscape fragmentation, isolation of habitat patches, noise, pollution, type and availability of food resources, human activities, vegetation quality in habitat patches. . .) that only species that have a (pre-) adapted way of life are able to tolerate them. Croci et al. [15] suggested that the urbanization filters bird species on the basis of their traits. That biological filter effect of urbanization seems to be a key determinant explaining which passerines can be found in town, urban adapters, and which cannot, urban avoiders. Studying bird avifauna at local and regional levels in France, Croci et al. [15] found 45 urban adapters that were mainly species that preferred forest (15 species) or meadow (14 species) habitats rather than open landscapes or aquatic habitats. The habitat availability in cities is a key determinant of the biological filter that urban constraints play on bird species from natural areas. Global abundance of species is not the main factor explaining their presence in cities. Indeed, urban adapters and avoiders were not associated with any of the modalities of the number of species pairs. Geographic distributions of urban

adapters were especially wide and involved more diverse biogeographic areas than urban avoiders generally from temperate climates.

Most species with high nests are associated with tree availability and, therefore, forest habitats, whereas nesting at low or medium heights is often correlated to shrubby, aquatic, or open and appeared as gregarious species. Being with congeners landscapes, omnivorous species were at an advantage in town, whereas granivorous species were at a disadvantage. Eating a variety of food items permits an exploitation of new resources linked to the town, such as garbage. Croci et al. [15] observed also that at the contrary of urban avoiders, urban adapters did not especially present a plumage coloration dimorphism and that urban avoiders were associated with more than two clutches per year and less wingspan when compared to urban adapters. Urban adapters seemed to have larger life expectancy than urban avoiders and were more sedentary that may enhance opportunities to learn from others birds experience, for example, for food location or predation avoidance, and thus, be at advantages in new environments such urbanized areas. Urban adapters also molt once a year whereas urban avoiders molt two times. All these traits lead us to believe that during the breeding season, urban avoiders have not much resources as urban adapters to allocate for adaptation to urban areas.

Homogenization

Biotic homogenization is the process by which the similarity of a biological variable increases across time and space. According to the nature of the variable, homogenization is qualified of taxonomic when there is an increase of the similarity of species between biotopes, functional when there is an increase of the similarity of biological traits (e.g., biological characteristics), and genetics when there is an increase of the similarity of the gene pool.

Each eco-region presents its own pool of species; however, in town the species are often the same [5]. McKinney [44] suggests that the urbanization modifies the community of species, decreasing the specialist species (increasing the generalists) and increasing alien species. Consequently, the similarity between

community increases with urbanization and gives biotic homogenization. In USA the part of alien exotic species is high and can explain a large part of the homogenization; in Europe, alien species are not so numerous [11] and the homogenization is linked to the increase of similar generalists. The explanations could be obtained in the similarity of the urban variables through the world (light, buildings, laws, climate, etc.).

Opportunities to Connect City Actors with Urban Nature

City Planning

The overall shape of cities has a large impact on the extent to which wildlife can colonize city environments, and to which humans can experience these plants and animals. On the one hand, there are the circular-shaped cities, of which the urban fringe – the zone where city and rural nature may interact – is minimal. Besides, the distance from the rural habitats to the city center of such cities is large, and as a result wildlife has to overcome many barriers to colonize inner-city areas. On the other hand there are starfish-shaped cities, where in between built-up areas there are so-called green wedges that may penetrate all the way to the city center. These green wedges often are remnants of former natural stream habitats or other, linear-shaped natural structures that were conserved during the urbanization process. In these starfish-shaped cities, wildlife can much easier migrate through the city environment. Moreover, for citizens the proximity of green in these green-wedge cities is much higher than in circular-shaped cities.

At a next level, it is the design of the “green within the urban area” that has great influence on the abilities of citizens to interact with nature. Within the domain of green space planning, the city’s internal major green structures are planned. The challenge is to find a balance between the portions and configuration of built-up area and those of urban green. From an estate development point of view, one could aim for a maximum portion of built-up area. Although this seems economically favorable at first sight, from a quality-of-life perspective a minimum amount of urban green is demanded to make that people like to live and work in such cities. Urban planners and

landscape architects, therefore, plan for green structures as public gardens and parks in between new residential and business areas to provide recreational opportunities and support the visual qualities of the built-up areas.

From the wildlife point of view, the way in which green structures are planned is crucial. Not only the amount and size of green structures, but also their mutual cohesion and their connectivity with the rural hinterland determines the habitat suitability of city environments. If urban planners aim to optimize human-nature interactions in the city, they should consider that continuous green structures are best to support wildlife movements, and thus enable plants and animals to inhabit the areas where people live and work. Thereby, wildlife will not discriminate between public or private green (as long as the habitat quality is fine), so connecting public parks with private garden complexes would favor wildlife [29].

Another aspect to take into account is that different plant and animal species may use different parts of the urban green as their habitat. Forest species (like woodpeckers) perceive large open green areas (e.g., grassland or swamps) as nonhabitat and rely on forest and trees structures for their habitat and dispersal opportunities. Other species may prefer swamp vegetation of river banks (e.g., dragon flies), or the flower-rich vegetation of extensive grassland (e.g., butterflies). To support a rich diversity of plant and animal species in the city environment, interconnecting similar types of biotope (forest with forest etc.) is necessary.

To some extent, peri-urban areas may determine the richness of urban nature. Peri-urban areas are the rural areas that are located adjacent to the city. Snep et al. [65] illustrated for butterflies that such peri-urban areas could act as source areas to strengthen nature in the inner-city. With sufficient habitat (in quality and quantity), local butterfly populations may thrive. A surplus of these butterflies may disperse from the peri-urban areas into the city using the urban green structures as dispersal corridors. City planners could take advantage of the natural value of the peri-urban area by tuning the type and structure of the urban green with the peri-urban nature. By doing so, they may optimize the opportunities for peri-urban wildlife to colonize the city.

Different Opportunities for Different Parts of the City

The public green and water structure in cities can be considered as the basis for the city's ecological functioning, due to its size and connectivity. Public green areas with predominantly lawn and solitary trees have little habitat value for the urban wildlife and its experience by citizens. If the urban green is however designed and managed in a more ecological way, a whole array of plant and animal species can be accommodated. Especially the abundance of brush and shrub vegetation containing native plant species will contribute significantly to the habitat quality of the urban green. This is, as these vegetation layers act as reproduction habitat for birds, butterflies, dragon flies etc. Also, the banks of streams and other urban water bodies have a good potential for wildlife, if not "engineered" with concrete sheet piling.

For most citizens, urban parks and water bodies are the places where "urban nature" can be experienced. Although these public areas can make up an important contribution to the city's wildlife habitat, there are

other, often private, areas that have good capacities to enhance the experience of urban nature by citizens. These areas are residential neighborhoods, school environments, and business districts.

Residential Neighborhoods A good way to (re)connect humans with nature is to enable citizens to experience nature in their own backyards. Many people like birdlife around their houses (especially songbirds), a conclusion that can be derived from the large portion of residential gardens with bird feeders and nesting boxes [17]. Abundant and diverse birdlife, however, is depending on more factors than only these specific bird features. To attract birds to residential areas, there should be enough habitat (being "urban green") in and around houses so birds have opportunities to eat, rest, reproduce, and gather. A high portion of urban green, as well as sufficient variety in plant species and vegetation structure, do not only enhance bird life, but also other animal groups as mammals (e.g., hedgehogs, bats) and insects (butterflies, (bumble)bees) (Fig. 6). Plants provide different habitat functions as food



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Urban green in the ecological housing area The Cherry Garden (NL), designed and maintained such that both biodiversity conservation as biodiversity experience is supported. The nectar plants and shrub provide habitat for butterflies, (bumble) bees, and song birds, the whole setting with the residential area is inviting for citizens to really experience the wildlife (Photo: Robbert Snep)

source (e.g., host and nectar plants for butterflies) and as reproduction or resting place (e.g., shrub and trees for bird nests). Native garden plants generally provide more habitat value for biodiversity than exotic garden plants, as the local animal life has coevolved with native plant species. Some exotic plant species are exceptions, like the cosmopolitan Butterfly bush (*Buddleja davidii*) that is a nectar source for butterflies in many parts of the world.

Incorporating small water bodies (garden ponds) in the gardens and neighborhood green structures adds extra habitat value to residential areas. Water habitats offer habitat for species with an entirely aquatic way of life (like fish and water plants), and also provide places to drink and forage for many terrestrial animal species. Additionally, they offer reproduction and nursery habitats for species with a partial aquatic way of life (e.g., amphibians, dragon flies).

On average, private gardens are too small to accommodate enough habitat, for example, a bird's territory. Animals therefore move between gardens to visit different resources. The urban design of the residential area as well as the vicinity of larger urban green areas have a great impact on the extent to which resources in a particular garden will be used by animals. If gardens are clustered, and fences between the individual gardens are permeable for wildlife, animal abundance will be more likely than in cases where gardens are walled and isolated from other green. Also, the presence of larger urban green areas in the vicinity of residential areas increase wildlife abundance, especially as there good opportunities for wildlife to exchange between urban green areas and residential neighborhood.

Finally, if wildlife is present in residential areas this does not automatically mean that citizens are aware of their presence, and as such are able to fully experience the diversity and phenomena of plant and animal life. On average, citizens often have low abilities to detect the presence of wildlife, as more and more citizens lack a history of growing up with wildlife [48]. There are two ways to increase wildlife experience opportunities:

1. To improve the visibility of wildlife for citizens, create habitat resources for wildlife in such way that wildlife will expose itself (to some extent) to

citizens. Well-known examples are nesting boxes and feeders for birds, other examples are bee trap nests, nectar hot spots for butterflies (e.g., group of butterfly bush), and garden ponds. A more sophisticated way is installing webcams in bird and bat boxes, or infrared cameras for nocturnal wildlife.

2. To improve the wildlife detection ability of citizens. Educate citizens in detecting wildlife, using binoculars (birds) and netting (insects, aquatic life) and tracking (ground-dwelling mammals) techniques. Often, (local) conservation groups are best equipped to stimulate and educate people on wildlife monitoring, using citizen science for conservation purposes.

School Environments Richard Louv [41] wrote a well-known and inspiring book, entitled "Last Child in the Woods," addressing the rapidly decreasing experience of (urban) youth with nature. This book gives a plea for (re)connecting youth with plant and animal life. School areas are perfect places to do so, as children will spend a large part of their early years in these environments. School yards can be designed and managed such that wildlife experience is optimized. Replacing a part of the school yard tiles by urban green that has good habitat value for butterflies, birds, (bumble)bees will stimulate children to explore nature. By actually involving children in the realization and management of this "school nature," they will perceive it as "their own" nature (Fig. 7).

Not only at school yards but also at other places in the direct vicinity of schools there are opportunities to let children experience wildlife. In the Dutch city of Eindhoven, more than 20 primary and secondary schools participate in the "school pond project," a municipal project in which ponds and nearby schools are managed and monitored by youth, supervised by local wildlife experts and teachers. During classes the children visit the ponds, making sure they are well informed about the developments of the local nature. If necessary, additional conservation measures such as habitat improvement are executed to enhance populations of local plants and animals. Linking the outdoor school nature with the actual school lessons on environment and biology offer opportunities to



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Greening project at a primary school, together with the children. Plants with added value for biodiversity are planted (*left*), attracting small wildlife that can be experienced (*right*) (Photo: Soontjens Stadsnatuur)

provide more background information about the local wildlife, and support children to understand the diversity of life and the working of the ecosystem.

Business Districts “Business districts” can be further classified as high-quality business sites, mixed business sites, logistic areas, heavy industrial areas, and seaport areas. Other names for these areas are business sites, business parks, industrial sites, industrial districts, or industrial estates. Opportunities for business sites to provide ecosystem services are now gradually being recognized. For example, recent studies have focused on how flat roofs, a typical feature of business site buildings, can be used (designed as green roofs) to reduce urban air pollution [80] or road traffic noise. Regarding biodiversity conservation at business sites, some initiatives are already under way in current practice. The US Wildlife Habitat Council (WHC) encourages corporations to voluntarily manage lands for wildlife and biodiversity protection, and certifies companies that substantially contribute to biodiversity conservation on their corporate lands [76]. Cardskadden and Lober [8] studied the benefits to corporations of participating in the WHC programme in terms of its influence on relationships with key corporate stakeholders including employees, host communities, environmental groups, and regulators. They report that at 164 sites, 95% of respondents indicated that wildlife

habitat programs had led to improved employee morale; 72% indicated improved relationships with environmental groups; 60% noted a positive effect on community relations; and 49% of respondents reported improved relations with regulators. These benefits were in addition to the annual cost savings reported by 50% of the programs. Besides, relationships with the community, government, and environmental groups led to better wildlife programs due to increased expertise.

In another example, the UK British Trust for Ornithology (BTO) awards companies that take specific measures to conserve bird diversity on their lands. The Business Bird Challenge began in 1994 and is a partnership between businesses, the BTO, and local communities which encourages biodiversity on business and industrial sites. Sites range from working quarries, power stations, and oil refineries to research establishments, company headquarters, and restored nature reserves. The aim is to maximize the potential of business sites for birds and other wildlife whatever the business site size.

In the Netherlands, Dutch Landscape Management promotes the integration of landscape elements and species conservation measures into business site development. They aim to raise awareness among municipalities and the business community, but also among project developers and designers,



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 8

Overview of how the greening of business sites with vegetation attractive for wildlife may improve both the business site as its urban and rural surroundings. The quality of life in adjacent residential areas can be enhanced by common wildlife originating from the business site [65]. The quality of work can be improved as the green enhances the aesthetic and recreation perception in the business environment [64]. The biodiversity in natural habitats near the business site can be enhanced as the business site may offer specific habitat for endangered butterflies and other species [66]

regarding opportunities and advantages that “green” business sites offer. They thereby focus on fitting business sites into their surrounding landscape, enhancing the ecological significance of business sites and increasing the accessibility of the sites for recreation purposes.

Business sites, often located at the city’s edge, can offer habitats for rare species (e.g., pioneer butterflies and amphibians), which mainly occur in the surrounding rural landscape, and for common species that also occur in the city [63, 65, 66] (Fig. 8). This implies that if biodiversity conservation is incorporated in business site planning, design, and management, the effectiveness of investments in conservation measures will increase if the target species and type and amount of habitat are attuned with the regional context of ecological networks.

Biodiversity conservation at business sites can be shaped in different ways, each with its own (socio) economic and environmental characteristics. There are different options for biodiversity conservation at business sites: green roofs and walls, a more ecological management of the conventional business green, temporary early successional vegetation on vacant parcels, and the design of ecological corridors and stepping stones throughout the business site. Results from a stakeholder survey on this topic suggest that implementing measures to enhance biodiversity may be acceptable only if combined with other green

functions (predominantly “recreation” and “health and well-being”) and if suited to the functional appearance of the business site environment (“external appearance” and “tidiness”) [64] (Fig. 9).

Future Directions: Integrating Wildlife Conservation in Sustainable City Planning and Design

Future directions in research, education, and practice on integrating wildlife conservation in sustainable city planning and design may focus on:

1. Climate-proof city green with ecological value
According to Pauleit et al. (see chapter “► [Green Infrastructure and Climate Change](#)”) urban green may support the resilience of cities toward climate change, as vegetation is able to cool (evaporation, shade) city environments and storage storm water (pervious soil). This demand for additional, climate-proof, urban green opens an opportunity to enhance the ecological quality of the city, if executed in the right way. As example, green roofs have excellent capacities to deal with heat and storm water (see chapters “► [Green Roofs, Ecological Functions](#)” and “► [Green Roof Infrastructures in Urban Areas](#)”), however the *Sedum* monoculture roof type – that is currently applied at large scale – has less ecological value than green roof types with more diversity in plant species (preferably,



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 9

Left: Illustration of how vegetation with ecological value (e.g., nectar plants) can be designed for a business site environment. *Right:* Actual urban green patch at a company with host plants for caterpillars of the Swallowtail (*Papilio machaon*) (Photos: Soontiens Stadsnatuur)



Biodiversity in Cities, Reconnecting Humans with Nature. Figure 10

Green roof vegetation at an inner-city apartment block in Eindhoven (NL). A nice appearance of the green is combined with a plant choice and maintenance that supports wildlife (birds, butterflies) and its experience by the residents (Photo: Soontiens Stadsnatuur)

native), soil type, and depth and other characteristics. A challenge for the future therefore is to design and manage the urban green meant for climate change mitigation purposes in an ecological way.

2. Urban agriculture with ecological value
Allotment gardens in city environments are an ancient phenomenon, subject to societal trends and thereby increasing and decreasing in popularity over time. A whole new global trend is the concept

of urban agriculture, beyond the traditional allotment garden. Urban farms produce food for the city, within the city itself. A well-known and quite extreme example are the urban farms at roof tops in New York City. Urban farms appeal to the current demand for “home-grown food.”

Urban agriculture provides habitat opportunities for urban wildlife and wildlife experience, if the agricultural practices are based upon biological principles (e.g., no pesticides). Urban farmers as well as visitors of these farms will thereby experience how natural processes like pollination are essential for growing food. Though this used to be basic knowledge among people for ages, citizens often have lost this knowledge. Urban farms are therefore excellent places to teach citizens about vital ecosystem services such as pollination and biological control. A future challenge is to integrate the urban agriculture concept in the city planning and design, as such that this phenomenon contributes to the basic understanding of citizens about the natural world they live in.

3. Urban energy and commodity production with ecological value

With successive energy and commodity crises worldwide, urban regions start to explore possibilities to produce their own energy and commodities, thereby decreasing their dependence from energy and commodity producers outside their region. There are several ways to produce energy, using different techniques.

One way to generate electricity or commodity comes from biomass. Although urban regions in general have a low production of biomass (e.g., prunings of tree and shrub vegetation from urban green management), this method may enhance the citizens' awareness about energy (“burning”) and commodity (“biorefining”) production, and also provides an added value to the city green. If in the near future urban biomass targets are set, this may lead to more shrubs and trees in the city, meaning more habitat for wildlife. The biomass topic represents future benefits that urban green may provide and that are currently not taken into account by urban planners and landscape architects in city development (see also chapter ► [Urban Forest Function, Design and Management](#)).

Another way of producing energy in cities is by solar panels at roof tops. These solar energy systems work most efficiently if the outside temperature is not too high. At roof tops covered with bitumen, the temperature will increase too much for optimal functional of the solar panels. At green roofs the direct surrounding of the solar panels is cooled by the vegetation (evaporation) and thus there is more efficiency.

Snep and Opdam [62] and Beatley [3] have addressed the opportunities to integrate natural values in urban planning and design quite extensively, like in Fig. 10. These publications focus on the “nature” aspect of urban green. There is however a much larger, global trend of “green cities”, in which “nature” is not mentioned explicitly. The term “green” here refers to “sustainable” (“green” being a modern alternative) or “vegetated” (“green cities” uses urban vegetation for its societal benefits). A challenge may be to connect these two worlds, to enable planners, (landscape) architects, project developers, and others to integrate wildlife conservation in the planning and design of sustainable cities. Future directions as mentioned above (climate-proof, urban agriculture, urban energy) can be seen as starting points to come to green, ecological cities with contain mutual benefits (both sustainable and natural).

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Bioethanol from Celluloses

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Article Outline

Glossary
Definition of the Subject
Introduction
Basics
Process Options
Enzymatic Hydrolysis Route
Future Directions
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Glossary

Bioethanol Ethanol produced by fermentation of sugars from plant materials, for example, sugar, starch, or cellulose.

Enzymatic hydrolysis A reaction where enzymes are used to catalyze splitting of molecules to smaller units by addition of water. Here, enzymatic hydrolysis refers to splitting of cellulose to glucose.

Ethanol fermentation The use of microorganism, in most cases yeast, for conversion of sugars to ethanol.

Flow-sheet design The use of computer programs for design and/or rating of complex production facilities, usually based on a conceptual drawing (flow sheet) of the process.

Lignocellulosic material A common name for plant biomass containing cellulose, hemicellulose, and lignin (e.g., hardwood, softwood, straw, bagasse).

Pentose fermentation Fermentation of sugars containing five carbon atoms, like xylose and arabinose, which are the main constituents in the hemicellulose fraction in agricultural residues and hardwoods.

Pretreatment Lignocellulosic material is by nature very recalcitrant to degradation. By pretreating the material, the structure is made more accessible for degradation by enzymes or microorganisms.

Process integration To design the unit operations involved in a process while considering the interaction between the units and to combine them in an optimal way. For instance, efficient use of heat and power is made possible by utilization of, for example, waste heat internally (in the plant), or externally (in a nearby plant), which can diminish requirement for expensive equipment, such as steam boilers.

Second-generation bioethanol Ethanol produced – in a sustainable way – from lignocellulosic materials (e.g., forest or agricultural materials).

Definition of the Subject

Bioethanol can be produced by fermentation of sugar present in the carbohydrate fractions (i.e., hemicelluloses and cellulose) available in all lignocellulosic materials. These could be agricultural residues (e.g., wheat straw, corn stover, sugarcane bagasse), forest residues (e.g., branches, tops, saw dust, thinning material), and energy crops (e.g., salix, hemp, Miscanthus, switchgrass).

To make ethanol from cellulosic materials is very similar to making ethanol from starch. First, the carbohydrates, hemicelluloses and cellulose, have to be hydrolyzed to monomer sugars and after that fermented to ethanol by a microorganism (e.g., yeast). There are, however, two major differences compared with starch ethanol:

- The structure of the lignocellulosic material is more difficult to break down due to stronger bonds between the sugar molecules in cellulose and the interaction between cellulose, hemicellulose, and lignin.
- While starch and cellulose are made up entirely of glucose, hemicelluloses comprise a variety of sugars, both pentoses (i.e., sugars with five carbons) and hexoses, which makes it difficult to find a single microorganism that can ferment all of these sugars.

This makes production of bioethanol from lignocellulosic materials much more complex than starch-based ethanol production. A third factor that differs is the presence of lignin, which protects the carbohydrates from degradation and makes enzymatic hydrolysis of the carbohydrates more difficult. However, having a lignin coproduct is also a possibility to improve the process economy as it can either be used as a valuable coproduct for chemical production or used for heat and power production as it has a higher heating value than the original biomass.

Introduction

Ethanol is currently the dominating renewable biofuel within the transport sector. It has been introduced on a large scale in Brazil, the USA, and some European countries and the production is expected to continue increasing during the years to come. The global production of ethanol in 2009 reached 73.9 billion liters [1]. Ethanol can easily be integrated in the existing land transportation infrastructure as a blend with gasoline, up to 20% ethanol, or as a neat alcohol in dedicated engines, taking advantage of the higher octane number and higher heat of vaporization. It is also an excellent fuel for future advanced flexi-fuel hybrid vehicles.

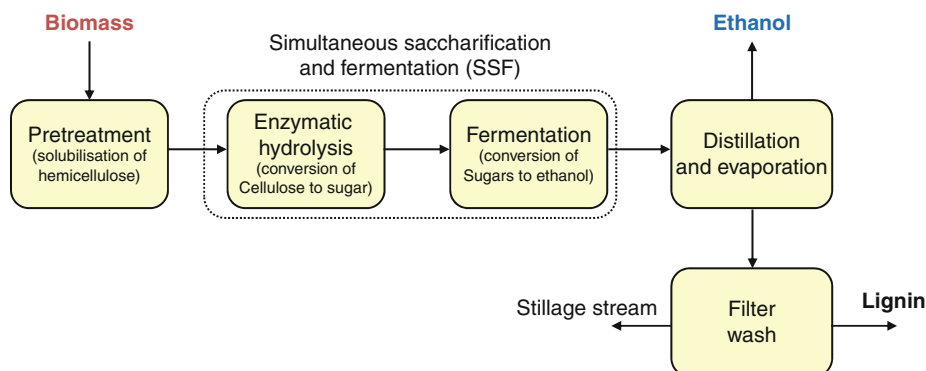
Ethanol can be produced through fermentation from a variety of sugar-containing crops such as

sugar beet, sugarcane, sweet sorghum, and fruits; starch-containing crops such as corn, wheat, and potatoes; and so-called lignocellulosic material such as agricultural wastes, wood, and municipal waste. Ethanol produced in this way is sometimes referred to as bioethanol.

The production of ethanol from sugar and starch is a well-established technology, which has been used for many years mainly for production of alcoholic beverages, but also for fuel ethanol in the last few decades. Currently, ethanol for the fuel market is produced from cane sugar (Brazil) or corn starch (USA) at more or less competitive prices. However, this raw material base, which also has to be used for human needs and animal feed, will not be sufficient to meet the increasing demand for fuel ethanol, and the reduction of greenhouse gases resulting from use of sugar or starch-based ethanol is not as high as desirable [2].

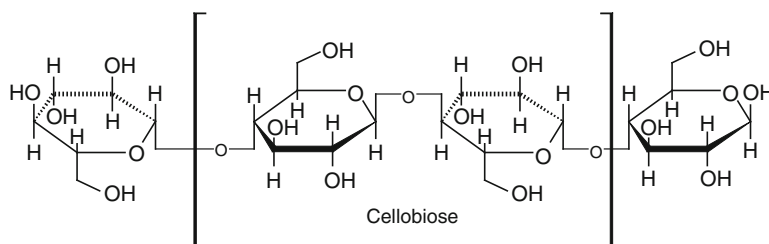
It is, therefore, a general opinion that future expansion has to be based on bioethanol from lignocellulosic material, which is usually called second-generation bioethanol (2G). These raw materials are sufficiently abundant and also available worldwide. They generate very low net greenhouse gas emissions and thus helping to reduce environmental impacts. However, processes for the production of ethanol from lignocellulosic materials are much more complex and not yet fully developed although several pilot plants and some demo plants have been in operation during the last couple of years. The main by-product of the processes is a solid residue consisting mainly of lignin, which can be used as a fuel, where the market is basically unlimited, or to make products of higher value in order to improve the process economy.

A process for bioethanol from lignocellulosic material consists of the following main steps: Hydrolysis of the carbohydrates (i.e., cellulose and hemicelluloses), fermentation of all sugars to ethanol, separation and upgrading of the ethanol to water-free ethanol, wastewater treatment, and combustion of the solid residue for production of steam and electricity required for the process (Fig. 1). The various process steps can be performed in many different ways and also the overall process configuration can vary. Furthermore, the ethanol process can be integrated with other types of industrial processes. A selection of important possibilities is described below.



Bioethanol from Celluloses. Figure 1

Simplified process for production of ethanol from lignocellulosic materials



Bioethanol from Celluloses. Figure 2

Cellulose chain

Within the explanations given below, the principles for ethanol production from cellulosic materials, recent developments in the bioconversion processes, and future challenges are outlined. First, characteristics of biomass in general are presented together with typical material compositions for various lignocellulosic feedstock, followed by a summary of different process options for hydrolysis of biomass. This chapter focuses on one option – the enzymatic route – which is covered in more detail with some important methods for pretreatment of biomass. In a process, hydrolysis is followed by fermentation of sugars, which is an area with intense research. Full-scale plants are considered next and the necessity of process intensification and process integration are discussed in depth with a number of examples.

Basics

The composition of lignocellulosic materials differs from one species to another. However, the main

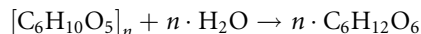
constituents are of the same type: about 50–60% carbohydrates in the form of cellulose and hemicellulose, 20–35% lignin, and some other valuable components like extractives, fatty acids, and ash.

- Cellulose* is the major component in the cell wall of plant cells consisting of linear chains of linked glucose units and it is the most abundant macromolecule on earth. The degree of polymerization (i.e., the number of glucose units) vary between 2,000 and 20,000. Every glucose unit is rotated 180° with respect to its neighbors and linked by β -1,4 glycosidic linkages, making the repeating unit the disaccharide cellobiose (Fig. 2). The linear chains associate strongly via intra- and interchain hydrogen bonding, which causes aggregation into so-called microfibrils with a largely crystalline structure combined with some amorphous regions. These microfibrils are highly stable and resistant to chemical attack, which makes cellulose insoluble in most common solvents, including water, and also very resistant to (enzymatic) hydrolysis.

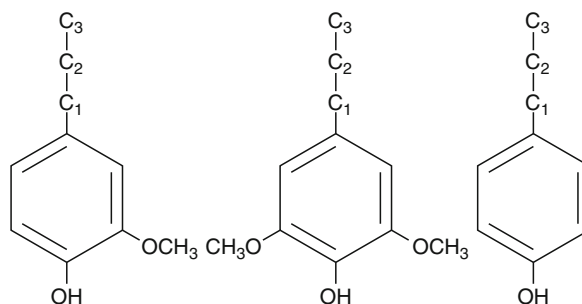
- *Hemicellulose* consists of short, highly branched chains of heterogeneous polysaccharide sugars, comprising both five-carbon sugars, called pentoses (usually D-xylose and L-arabinose) and six-carbon sugars, called hexoses (D-galactose, D-glucose, and D-mannose) [3]. The branches also contain other groups (e.g., acetyl groups and glucuronic acid). The degree of polymerization is much lower than for cellulose, around 200. Hemicellulose is more hydrophilic and easier to hydrolyze than cellulose. The main carbohydrate in hemicelluloses from agricultural crops and hardwoods is xylose, while mannose is dominating in softwood (Fig. 3).
- *Lignin* is the major non-carbohydrate component in lignocellulosic materials comprising a highly complex, three-dimensional polyphenolic compound. It is closely attached to the cellulose and the hemicellulose and is responsible for the remarkable strength of plants, especially trees. The primary building units of softwood lignin are mainly guaiacyl, with minor amounts of syringyl and

p-hydroxy-phenylpropane units, while hardwood contains more syringyl units (Fig. 4).

Cellulose can be hydrolyzed to glucose according to the following chemical formula:

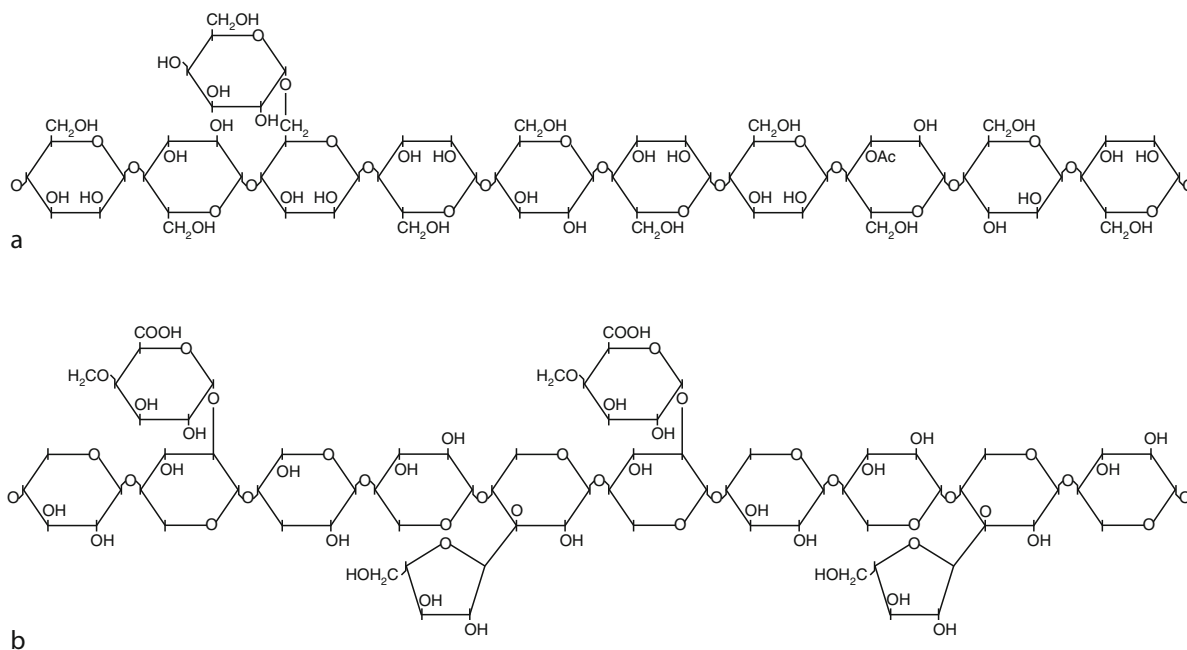


that is, theoretically 1 kg of cellulose results in 1.111 kg of glucose.



Bioethanol from Celluloses. Figure 4

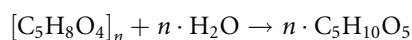
The guaiacyl (left), syringyl (middle), and *p*-hydroxyphenyl (right) units in softwood lignin



Bioethanol from Celluloses. Figure 3

Example of hemicellulose chains. (a): o-acetyl-galactoglucomannan; (b): arabinogalactan-4-O-methylglucuronoxylan

This is also valid for hydrolysis of the anhydrosugars in the hexose fraction in hemicelluloses, while the hydrolysis of the pentose fraction would be:



that is, theoretically 1 kg of xylan (or arabinan) may yield 1.136 kg of xylose (or arabinose).

The sugars can then be fermented to ethanol using some microorganism, like yeast or bacteria, which theoretically can result in 0.51 kg of ethanol and 0.49 kg of CO₂ from 1 kg of sugar (either hexose or pentose) according to:



Table 1 shows typical compositions of some selected lignocellulosic materials. The composition may differ depending on where the biomass grows and at what time of the year it is harvested. For three of the materials, the standard deviation is given based on at least five different samples to show the extent of variations. The hemicellulose in agricultural crops and hardwood is primarily composed of pentose sugars, while softwood hemicellulose has a large fraction of the hexose mannan. This is reflected in the amount of ethanol that can theoretically be produced from 1 t of dry matter for the various biomasses according to the formulas given above (Table 1). It is quite clear that pentose

fermentation is not so important for efficient utilization of softwood while it may constitute up to 40% of the potential ethanol production from agricultural crops like corn stover and wheat straw or from grass like switchgrass.

For spruce up to 50% of the energy can theoretically be obtained in the ethanol (if all the sugars are converted to ethanol) and another 35% is obtained in the coproduct lignin. In a real process, less than this theoretical yield will be obtained because of losses in the conversion and due to the needs for energy, heat, and power in the process.

In a longer perspective, lignin may be used for production of chemicals. Lignin is a very complex molecule, which contains numerous aromatic compounds of which some have interesting properties. In contrast to the coproduct from starch-based ethanol production (DDGS, which is used as animal feed), there is no real limitation for the use of the lignin-rich residue as a fuel. About the same ethanol yield could be expected from different crops, although agricultural residues in general contain less lignin; thus, the energy contribution from the lignin part will be lower.

Besides the carbohydrates and lignin, most lignocellulosic materials also contain other compounds like extractives and ash. The agricultural crops may also contain some residual fractions of starch, proteins, and pectin. The amounts of these compounds vary a lot between different types of lignocellulosic materials

Bioethanol from Celluloses. Table 1 Composition of various lignocellulosic materials in percentage dry basis (values in brackets are standard deviations from several studies)

	Glucan	Mannan	Galactan	Xylan	Arabinan	Lignin	Ethanol C6	Ethanol C5	Reference
Pine	43.6	10.8	2.2	6.6	1.6	26.8	411	28	[4]
Spruce	48.7 ± 2.60	12.6 ± 0.55	2.4 ± 0.76	6 ± 2.11	1.5 ± 0.53	28 ± 0.47	463	29	[5]
Aspen	50	2	1.5	18	4	18	389	164	[6]
Poplar [1]	43.8	3.9	1	14.9	0.6	29.1	354	115	[7]
Poplar [2]	45.1	1.7	1.5	17.8	0.5	21.4	351	136	[7]
Willow	43	3.2	2	14.9	1.2	26.6	350	120	[8]
Corn stover	37.5 ± 2.2	0.6 ± 1.1	1.6 ± 1	21.7 ± 2.1	2.7 ± 1.6	18.9 ± 2.6	288	181	[9]
Sugarcane bagasse	40.2	0.5	1.4	22.5	2	25.2	306	182	[10]
Wheat straw	32.6	0	0.8	20.1	3.3	26.5	243	174	[11]
Switchgrass	34.2 ± 2.1	0.3 ± 0	1.4 ± 0.5	22.8 ± 1	3.1 ± 0.5	19.1 ± 1.7	261	192	[9]

and are also affected by the geographical site of cultivation, the soil, and the season. These compounds are usually not discussed very much in research on ethanol production but must of course be considered in full-scale processes. They may both be an asset, in terms of coproduct value, and a problem due to influence on the biological conversion steps.

Process Options

There are several options for a lignocellulose-to-ethanol process but, regardless of which is chosen, the following challenges must be addressed [12]:

1. Efficient depolymerization of cellulose and hemicellulose to soluble sugars.
2. Efficient fermentation of a mixed-sugar hydrolysate containing six-carbon (hexoses) and five-carbon (pentoses) sugars as well as fermentation inhibitory compounds.
3. Advanced process integration to minimize process energy demand.

4. Integration with external processes for cost-efficient use of lignin and residual organic matter.

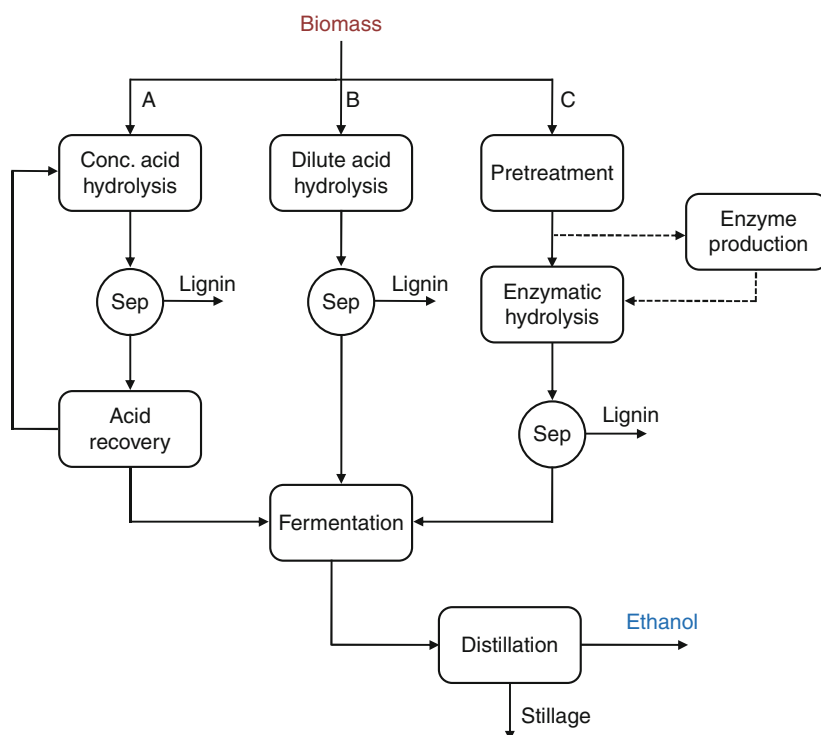
The first step in the conversion of biomass to ethanol is size reduction and hydrolysis of the carbohydrates. This can in principle be performed in three ways (Fig. 5):

- (a) By use of concentrated acid hydrolysis
- (b) By dilute-acid hydrolysis
- (c) By enzymatic hydrolysis

Either way, the target is to access the cellulose and hemicellulose to generate individual sugar monomers for the fermentation process. In the following section, a summary of various methods is presented.

Concentrated Acid Hydrolysis

Concentrated acids (e.g., sulfuric, hydrochloric, hydrofluoric, and nitric acid) can be used to dissolve native cellulose at rather low temperatures. If the mixture is diluted with water and heated, the cellulose is



Bioethanol from Celluloses. Figure 5

Different routes for hydrolysis of lignocellulosic materials

hydrolyzed to monomer sugar. This has been known since the 1880s [13] and has been used in several full-scale processes during the twentieth century. For example, in Germany, several full-scale plants for hydrolysis of wood using concentrated hydrochloric acid (40% HCl) were operated during World War II. Several plants based on concentrated sulfuric acid were commercialized in the middle of the twentieth century in the former Soviet Union and in Japan [14]. However, these processes have only been run under times of national crisis and the products (e.g., chemicals, fuel, and feed) were not competitive on international markets.

The process results in rather high yields, but the large amount of acid used creates several problems such as corrosion and pollution. Furthermore, the dilution of the acid in the second hydrolysis step requires high amounts of energy for acid recovery. Nevertheless, the process using concentrated sulfuric acid has gained renewed interest due to the inventions of new methods to separate the acid from the sugar solution, based on ion exchange.

Dilute-Acid Hydrolysis

Dilute-acid hydrolysis of biomass is the oldest technology for conversion of cellulosic materials into sugars. The first commercial plant for production of ethanol from wood based on acid hydrolysis of sawdust, and using diluted sulfuric acid, was built already at the end of the nineteenth century. Since then, several plants have been operated in the USA, Japan, Germany, and the former Soviet Union [15]. There are still some plants operating in Russia. Most of the old plants were run with one-stage hydrolysis using some kind of percolation, where liquid is flushed through the reactor to remove the sugars formed. The main drawback was a moderate yield of sugars and also very dilute sugar solutions, which required a considerable input of energy in the distillation step for recovery of ethanol.

After 1973, several research programs were started around the world to improve the yield and increase the sugar concentration of this process. In the first step, hemicellulose is hydrolyzed under milder conditions (170–190°C), while in the second step the cellulose is hydrolyzed under more severe conditions (200–230°C). However, the high temperatures required for

hydrolysis of the cellulose also result in sugar decomposition, which not only decreases the yield but also produces compounds that inhibit the microorganisms in the fermentation step. Also for a two-step acid hydrolysis, the overall sugar yield is usually lower than 60% [16].

Enzymatic Hydrolysis

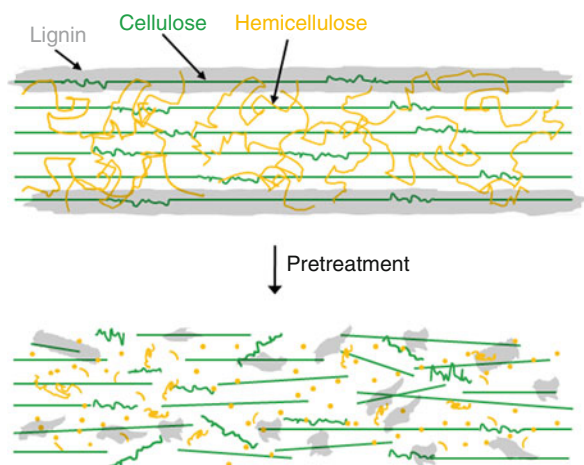
One of the most promising process alternatives for production of sugar for fermentation from woody materials is the enzymatic process [17–19] because of its potential for high yields. Figure 5 provides a schematic view of the process. The enzymatic hydrolysis process comprises the following main steps: pretreatment of biomass, enzymatic hydrolysis, including enzyme production, fermentation of all sugars, ethanol upgrading, wastewater treatment, and heat and power production.

However, the hydrolysis of lignocellulose using enzymes can be hampered by the very low reaction rate. Lignocellulosic materials are by nature very recalcitrant and not very many microorganisms can degrade them in a fast and efficient way. The main reason is the requirement of a whole array of enzymes, each having more or less specific activity on a certain type of polymeric fragment, such as cellulases, xylanases, mannanases, and lignases.

It is, therefore, of vital importance to pretreat the material to alleviate the enzymatic attack on the structure. The complexity and interconnectivity of the polymers constituting lignocellulose materials makes it necessary to open up and/or partially hydrolyze the structure (Fig. 6). After pretreatment and enzymatic hydrolysis, the process steps are very similar to what is used in concentrated or dilute-acid hydrolysis processes (Fig. 5).

Enzymatic Hydrolysis Route

In general, enzymatic hydrolysis can be considered as more favorable to use than acid hydrolysis because of the milder conditions and higher potential yields of sugars. It does, however, require the pretreatment step, which can constitute a substantial fraction of the overall cost. Therefore, the enzymatic hydrolysis route is discussed below in more detail; however, the parts after pretreatment and enzymatic hydrolysis are to



Bioethanol from Celluloses. Figure 6
Schematic view of the effect of pretreatment

a large extent valid also for the other two process alternatives (i.e., concentrated and dilute-acid hydrolysis).

The pretreatment step is perhaps the single most crucial step as it has a large impact on all the other steps in the process (e.g., enzymatic hydrolysis, fermentation, downstream processing, and wastewater handling in terms of digestibility of the cellulose, fermentation toxicity, stirring power, energy demand in the downstream processes, and wastewater treatment demands).

Pretreatment Methods

Pretreatment, to be effective, should have a number of features [20]. It has to:

- Result in high recovery of all carbohydrates.
- Result in high digestibility of the cellulose in the subsequent enzymatic hydrolysis.
- Produce no or very limited amounts of sugar and lignin-degradation products [21]. The pretreatment liquid should be possible to ferment without detoxification.
- Result in high solids concentration as well as high concentration of liberated sugars in the liquid fraction.
- Require a low energy demand or be performed in a way so that the energy can be reused in other process steps as secondary heat.
- Require low capital and operational cost.

During the last 2 decades, a number of alternatives have been proposed for pretreatment of various substrates. This can be achieved in various ways, using either physical (e.g., milling, grinding, or irradiation), or chemical (e.g., alkali, dilute acid, oxidizing agents, or organic solvents) methods, or (something in between) physicochemical (e.g., steam pretreatment/ autohydrolysis, hydrothermolysis, or wet-oxidation) methods. This classification is rather vague since in some cases it is difficult to put a label on the chosen pretreatment type [21–26]. Some methods are more efficient than others when it comes to yield and recovery of the fractions. Also, some methods are better suited for hardwood or agricultural residues than for pretreatment of softwood, probably because of the different lignin structures in softwood as compared with that in hardwood or agricultural substrates. Below, a selection of important pretreatment methods is summarized.

Physical Methods Chipping, milling, and grinding are methods that aim at reducing particle size and thus increase the surface area exposed to enzymatic attack. The biomass is turned to a fine powder of some microns in size. To some extent decrystallization occurs, which also improves the hydrolysis rate. However, in order to achieve a high digestibility in the enzymatic hydrolysis step very small particles are required, which makes high power consumption unavoidable. Actually, it can be even higher than the theoretical energy content that is available in the biomass [27]. An interesting option could be physical treatment in an extruder combined with heating and addition of chemicals in which case the power requirements can be smaller [28].

Chemical Methods The most common chemical method is to use dilute-acid pretreatment, in which the material is impregnated by soaking (or by spraying) using a dilute strong acid. By heating the wetted material to temperatures in a range of about 140–200°C for a period of a few minutes to an hour, partial hydrolysis occurs resulting in monomeric sugars from the hemicellulose part of the substrate. Typically, sulfuric acid at concentrations less than 4% by weight has been added. The frequent use of H_2SO_4 is due to it being rather inexpensive and efficient. A drawback is the generation

of toxic compounds, if the pretreatment is too harsh, that may be detrimental to the fermenting organism [29–31]. Also, the sulfur may pose a problem if not taken care of properly. The residual lignin-rich fraction can be used for heat generation, but if the sulfur content is too high, it can only be used with careful desulfurization of the effluents. Too high sulfur content in the final ethanol can cause malfunctioning of the fuel-injection nozzles in some engines.

Pretreatment using alkaline conditions are commonly performed at lower temperatures and pressure than is acid pretreatment. When the material is soaked in an alkaline (e.g., hydroxides of sodium, potassium or ammonium), pore swelling results. As a consequence, the internal surface area increases, which makes the carbohydrates more accessible for the enzymes. Besides the area increase, breaking of the lignin–carbohydrate bonds takes place, which also allows for the enzymes to attack the cellulose and hemicellulose chains. Alkaline pretreatment has been shown to be more efficient for agricultural residues and herbaceous crops than for woody materials, as the former type of substrates contain less lignin. To reach similar results using woody materials, the cooking conditions must be much more severe, similar to the Kraft process for pulping.

Lime pretreatment is an alkaline method, which is useful when agricultural or hardwood residues are involved [32, 33]. Due to its relatively low cost, it has become an interesting alternative; also since it can be recovered as solid CaCO_3 when reacted with CO_2 . The calcium carbonate can then be recovered and converted to lime again using a kiln. A disadvantage using calcium-containing salts is the risk for precipitations of, for instance, calcium oxalate, which is a well-known problem in the pulp industry. When process streams containing calcium salts are recirculated in the pulp plant, precipitation often takes place on heat-exchanger surfaces causing scaling.

Organic solvents such as methanol, ethanol, acetone, glycols, or phenol, with small amounts of an inorganic acid catalyst (e.g., HCl or H_2SO_4), comprise foundation for the organosolv method [34]. This option makes use of that lignin dissolves in the organic phase, where it can be recovered using various technologies. It is essential to recover the solvent both for economic and for environmental reasons, but also because the solvent itself may be inhibitory in the

enzymatic hydrolysis and the fermentation steps. When ethanol is used as solvent the recovery is facilitated as this is part of the ethanol production plant.

Physicochemical Methods This category involves methods that combine a physical and a chemical effect (e.g., steam pretreatment with addition of a catalyst, hydrothermolysis, wet oxidation, and ammonia fiber explosion (AFEX)).

Steam pretreatment (sometimes called steam explosion) is commonly used for pretreatment of lignocellulosic materials. It is, in essence, a chemical method very similar to dilute-acid hydrolysis, but usually performed at higher dry-matter contents than is dilute-acid hydrolysis. The typical temperature range is between 160°C and 240°C , with a treatment time of 1–20 min, after which the pressure is rapidly released (“exploded”) and the material transported to a flash-off vessel. It is well suited for most materials, also for softwood. In this case, a small amount of acid catalyst is added to improve hemicellulose hydrolysis; however, when treating agricultural residues or most hardwood species, the inherent acetic acid content is enough to initialize hemicellulose hydrolysis, so-called autohydrolysis. In this case, the final pH is usually around 3–4, while it is set to 2 or less when mineral acids are added. The steam pretreatment method has been tested in pilot- and demo scale.

Hydrothermolysis is similar to steam pretreatment but is performed using more water and usually at slightly lower temperatures and lower dry-matter content. The result of hydrothermolysis is a liquid containing solubilized material, of which much is in its oligo- or polymeric form [35, 36]. This is usually not a problem if the enzymes added during the subsequent hydrolysis are selected to break down the fragments to monomers. For example, autohydrolysis of straw in larger scale has been demonstrated [37]. A variation of hydrothermolysis is the wet-oxidation procedure [38], where air or oxygen is added. This method is suited for materials having low lignin content as the yield has been shown to decrease with increasing lignin content. A drawback is that the lignin is oxidized causing loss of valuable material.

Ammonia fiber explosion (AFEX) is an alkaline method, which operates at elevated pressures, similar to steam pretreatment. However, in the AFEX method,

instead of water, liquid ammonia is added and the substrate is treated for 10–60 min at around 100°C or less [39, 40]. The resulting material contains very much of the carbohydrates in their polymeric forms. If the material is to be fermented, hydrolysis must be performed. However, the material has interesting properties in terms of water-holding capacity and gel formation ability, which can lead to new biodegradable polymer materials (e.g., barrier films and capsules controlled release of drugs). Like other alkaline methods, AFEX performs best on agricultural waste [41, 42], while its efficiency toward wood is lower, probably because of the higher lignin content. The ammonia must be recycled in the process to make it feasible, from economic and environmental aspects.

Biological Methods Biological pretreatment can be performed using microorganisms or individual enzymes to degrade the biomass to polymers [43]. The actual degradation is usually performed using white-rot fungi or brown-rot fungi, which breaks down the lignin or the cellulose and the hemicellulose part, respectively. The method as such has not been attracting too much attention, mainly because some of material is lost in the breakdown process, but also since biological degradation is a slow process and, therefore, would require large treatment units. It would be possible to use the fungi as a first step, while the raw material is stored in piles prior to the main pretreatment step.

Ionic Liquids A rather new approach is to use ionic liquids [44] to fractionate the polymers of lignocellulosic materials. Ionic liquids (IL) are salts, typically consisting of a large organic cation (e.g., 1-butyl-3-methylimidazolium and a small inorganic anion moiety). They exist as liquids at room temperature and are chemically and thermally stable. They act by disrupting the bonds between cellulose, hemicellulose, and lignin thus dissolving the molecules, while forming very little degradation products. So far, it has been demonstrated using pure crystalline cellulose, but some work using straw has also been rather successful.

Before ionic liquids can be used commercially, a number of questions must be answered. It is still not clear how they influence fermenting organisms, although initial tests do not indicate any major problems. However, it is necessary to establish efficient

methods to recover the dissolved macromolecules from the ionic liquid, or, put in other words: how can one recycle the ionic liquids? Currently, the cost for ionic liquids is very high, which makes them less suited for use in production of bulk chemicals, such as ethanol. If, however, value-added chemicals (from hemicellulose or lignin) can be produced in conjunction with ethanol production, and efficient means to recycle the ionic liquids are found, they constitute a very interesting option.

Evaluation Having an array of different pretreatment methods to choose from makes it necessary to have tools for evaluation of the optimal process in terms of economic and operational feasibility. Not only must the pretreatment result in a well-treated substrate, but also the yields of the fractions have to be high. More severe conditions during pretreatment will cause greater degradation of hemicellulose sugars [45–47]. It is also necessary to consider the by-products formed and the impact they may have on the enzymatic hydrolysis and the fermentation steps. It is presently difficult to say that one method is very much better compared to another option without taking into account, for example, the type of raw material that will be used in the process or what by-products can be expected. Also, it is of importance for the economics of the process to consider utilization of the energy content in lignin for internal heating purposes or for the production of lignin pellets for off-site markets.

Several pretreatment methods (e.g., dilute-acid hydrolysis, SO₂-catalyzed steam pretreatment, controlled pH, AFEX, ARP (ammonia recycled percolation), and lime pretreatment) have been compared using the same batch of raw material and exactly the same procedure and conditions for assessment of the pretreated material. This investigation has been carried out for two different batches of corn stover [48] and for poplar wood [7]. The assessment was performed by determining the recovery of glucose and xylose both as monomeric and oligomeric sugars in the liquid after pretreatment and in the liquid after enzymatic hydrolysis of washed solid material (from pretreatment). The enzymatic hydrolysis was performed using solid material at a concentration of 1% glucan (which is a low concentration) and an enzyme dosage of 15 FPU/g glucan of the untreated material. Table 2 summarizes

Bioethanol from Celluloses. Table 2 Summary of studies on corn stover. Yield of sugars^a, in percentage of theoretical available in the raw material, after pretreatment and after pretreatment + enzymatic hydrolysis [48]

Method	Catalyst	Time and temperature	Pretreatment		Pretreatment + enzymatic hydrolysis	
			Xylose	Glucose	Xylose	Glucose
Dilute-acid hydrolysis	H ₂ SO ₄ 0.49%	20 min, 160°C	85.1 (82.8)	6.3	93.6 (91.2)	91.7
Steam pretreatment ^b	SO ₂ 3%	5 min, 190°C	37.1	8.6	91.8	95
Controlled pH	None	15 min, 190°C	57.8 (2.4)	5.6 (0.3)	81.7 (26.3)	85.2
AFEX	Conc NH ₃	5 min, 90°C	0	0	91.8 (77.7)	96
ARP	NH ₃	10 min, 170°C	47.2	0	88.3 (41.1)	90
Lime	CaO 0.08 g/g biomass	4 weeks, 55°C	24.4 (0.8)	1.6 (0.5)	76.4 (52.8)	93.1 (92)

^aBased on monomer and oligomer sugars obtained in the hydrolysate after pretreatment and in the enzymatic hydrolysis of pretreated material. Numbers in brackets are for monomer sugars only, when reported

^bPerformed for another batch of corn stover

Bioethanol from Celluloses. Table 3 Summary of studies on poplar. Yield of sugars^a, in percentage of theoretical available in the raw material, after pretreatment and after pretreatment + enzymatic hydrolysis [49]

Method	Catalyst	Time and temperature	Pretreatment		Pretreatment + enzymatic hydrolysis	
			Xylose	Glucose	Xylose	Glucose
Dilute-acid hydrolysis	H ₂ SO ₄ 2%	1.1 min, 190°C	62.4	23.9	71.7	86.7
Steam pretreatment	SO ₂ 3%	5 min, 190°C	74.4 (54.3)	3.1	83.7 (63.6)	100
Controlled pH		10 min, 200°C	58.1 (3.9)	2 (0.1)	95.7 (41.5)	55.9 (54)
AFEX	Conc NH ₃	10 min, 180°C	0	0	51.9	53.1
ARP	NH ₃ (39%)	27.5 min, 185°C	37.2 (0)	0.5 (0)	68.6 (31)	49.3 (48.9)
Lime	CaO 20%	120 min, 160°C	4.7 (0)	0.3 (0)	77.5 (65.1)	96 (90.6)

^aBased on monomer and oligomer sugars obtained in the hydrolysate after pretreatment and in the enzymatic hydrolysis of pretreated material. Numbers in brackets are for monomer sugars only, when reported

the results for the second batch of corn stover, which are very similar to those for the first batch. The total yield of sugars obtained with the different pretreatment methods was more or less the same, around 90% or more. The main difference is that the low pH methods, like acid hydrolysis and SO₂-catalyzed steam pretreatment, result mainly in monomeric xylose, while the high pH methods (like AFEX) result in a large amount of oligomeric xylose, which requires

also a whole range of hemicellulases in the enzymatic hydrolysis.

Table 3 shows the sugar yields from the poplar-wood study. The yield varies more for poplar than for corn stover. It is higher, especially regarding glucose, for the low pH methods with a glucose yield close to theoretical compared with the high pH methods with glucose yield as low as 50%. Also for poplar, the high pH methods result in more oligomeric xylose, with the

exception of lime. It should also be noticed that for poplar much more severe conditions, like a higher temperature, had to be used (Table 3) compared with the requirements for corn stover.

While many pretreatment methods have been investigated for agricultural waste and hardwood, the number of feasible pretreatment methods investigated for softwood is smaller. It appears that acid hydrolysis and steam pretreatment with acid catalyst are the most appropriate methods [20] to give high sugar yields from softwoods, which are much more recalcitrant than the other lignocellulosic materials. Acid hydrolysis and steam pretreatment with acid catalyst seem to be the methods that can be used for all types of raw materials and these are also the methods that have been most extensively used in pilot and demo plants. However, the drawbacks are the high equipment cost and the formation of inhibitors formed during pretreatment.

In most assessments of pretreated materials, a mixture of cellulases is used in the enzymatic hydrolysis step. Steam pretreatment of corn stover, with and without addition of SO₂, was assessed by enzymatic hydrolysis using ordinary cellulases supplemented with xylanases [49]. The additions of small amounts of xylanases had a major impact on the xylose yield and, surprisingly, even more on the glucose yield (Table 4).

The improvement of sugar yield in the enzymatic hydrolysis of corn stover by addition of xylanase was more pronounced for pretreatment methods that removed less xylose (e.g., AFEX) [50]. However, also for SO₂-catalyzed pretreatment, the increases in

glucose and xylose yields in the enzymatic hydrolysis were about 15% and 34%, respectively. This was also shown for poplar wood [51]. This shows the importance of not using standard methods when assessing pretreatment, but to actually optimize the combination of pretreatment and enzymatic hydrolysis, and preferably also fermentation.

It is important, however, to keep in mind that the assessments described above are not performed under realistic process conditions as the substrate concentration in the enzymatic hydrolysis was very low and the influence of possible inhibitors present in the pretreated slurry was avoided. For a correct evaluation, the fully integrated process must be considered as the various pretreatment methods result in different types of materials. Hemicellulose sugars can be obtained either in the liquid as monomer or oligomer sugars, or in the solid material to various extents; lignin can be either in the liquid or remain in the solid; the composition and amount/concentration of possible inhibitory compounds also vary. This will affect how the enzymatic hydrolysis should be performed (e.g., with or without hemicellulases), how the lignin is recovered, and also the use of the lignin coproduct. This means that all process steps have to be optimized taking into account the special features of the pretreated material, and then comparing the production cost for the various alternatives.

Enzymatic Hydrolysis

Enzymatic hydrolysis of lignocellulosic materials requires a multitude of enzymes, which have activity

Bioethanol from Celluloses. Table 4 Overall sugar yields as percentage of theoretical based on content in raw material after enzymatic hydrolysis of steam-pretreated corn stover (with and without impregnation with SO₂ [48])

Pretreatment conditions	Enzymatic hydrolysis using only cellulases ^a		Enzymatic hydrolysis using cellulases ^a with addition of xylanases ^b	
	Glucose	Xylose	Glucose	Xylose
170°C, 9 min + SO ₂	62.2	67	70.7	70.6
190°C, 5 min + SO ₂	83.2	70.5	96	73.9
190°C, 5 min, no catalyst	69.3	74.6	93.8	85.3

^aCelluclast 1.5 L and Novozyme 188 (both from Novozymes A/S Bagsvaerd, Denmark)

^bMultifect Xylanase (from Genencor) Int. Rochester, NY, USA)

Total amount of protein equal in all enzymatic hydrolysis

toward a variety of molecular groups. For example, to hydrolyze cellulose, at least three different types of enzymes must be present: endoglucanases, which disrupt amorphous areas of the molecule to create free ends; cellobiohydrolases that cleave cellobiose from both ends of the exposed chain to form cellobiose; and, finally, β -glucosidase that generates two glucose molecules from cellobiose. Most cellulases are end-product inhibited, that is, most cellulases are affected by cellobiose [52, 53], while β -glucosidase is particularly sensitive to glucose [54], resulting in an accumulation of these sugars, which slows down hydrolysis (or even stops it completely). Compounds that are generated in the pretreatment step can also have a negative impact on enzymatic hydrolysis. If the liquid fraction from the pretreatment step is replaced or if washed material is used for enzymatic hydrolysis, hydrolysis can be improved [55]. This improvement suggests that other inhibitory compounds than the sugars may play a vital role as inhibitor. Another important factor is the unproductive binding of the cellulase enzymes to lignin, causing the overall catalytic effect to be smaller.

There are many cellulase-producing species in nature, most of them various fungi. The maximum cellulase activity for most fungal-derived cellulases and β -glucosidase occurs at $50 \pm 5^\circ\text{C}$ and a pH of 4–5. During the last decade, much effort has been made to improve the overall activity of the enzymes and the yield of enzymes, but also production itself has been rendered more effective to decrease cost. Independently from ongoing cost-reduction efforts [56, 57], the production cost of enzymes is still rather high and requires further reduction. One way to achieve this is to use a fraction of the feedstock and/or the hydrolysate for on-site enzyme production by fungi or other microorganisms [58].

Some pretreatment methods leave the hemicellulose fraction more or less unaffected calling for additional hydrolysis using hemicellulases. The hemicellulose part of lignocellulosic materials requires other types of enzyme complexes for efficient hydrolysis. Since the raw material differs with regard to the composition of hemicellulose, ideally the enzyme cocktail should be prepared in a way that best meets the demand of the various materials. For example, agricultural residues require xylanases to be present, while it is preferable to have mannanases if the material is softwood.

The hemicellulase system includes among others endo-1,4- β -D-xylanases, which hydrolyze internal bonds in the xylan chain; 1,4- β -D-xylosidases, which attack xylooligosaccharides from the nonreducing end to liberate xylose; endo-1,4- β -D-mannanases, which cleave internal bonds in mannan; and 1,4- β -D-mannosidases, which cleave mannooligosaccharides to mannose. The side groups are removed by a number of enzymes: α -D-galactosidases, α -L-arabinofuranosidases, α -glucuronidases, acetyl xylan esterases and feruloyl, and *p*-cumaric acid esterases [59–62].

Enzymatic hydrolysis of lignocellulosic materials has been studied on a number of substrates and under various conditions [55, 63, 64]. Separate hydrolysis and fermentation (SHF) is an attractive idea since it allows for different conditions during hydrolysis and fermentation, though the choice between SHF and simultaneous saccharification and fermentation (SSF, which is described in detail below) has to be made after economic optimization. It is possible to have a higher temperature during hydrolysis to benefit from the higher activity of the enzymes at elevated temperatures. However, it is important to note that the stability of the enzymes is affected by temperature. It has been shown that it can be favorable to operate at lower temperatures to reach higher yields of sugars. For spruce the optimal temperature was found to be dependent on both residence time and pH, and the maximum degree of cellulose conversion, 69.2%, was obtained at 38°C and pH 4.9 for a residence time of 144 h [65]. The decision regarding maximum reaction rate, optimal stability, and residence time has to be made based on economic considerations. It is also desirable to operate at high solids content to reach sugar concentrations that will result in ethanol concentrations around 4%. However, increasing solids concentrations create technical problems, since it can be difficult to mix the material efficiently, especially in the initial phase of hydrolysis, when the viscosity can be very high [66, 67, 110].

Fermentation of Sugars

Fermentation is performed using a microorganism, usually yeast, which converts sugar to ethanol. The yeast *Saccharomyces cerevisiae* (sometimes referred to as baker's yeast) is today the prime choice in industrial

ethanol production from starch and sugar. It is a very robust microorganism, which has a high ethanol tolerance and is also rather tolerant to inhibitors produced during pretreatment of biomass. It has also a high ethanol productivity (up to $1.3 \text{ g g}^{-1} \text{ cell mass h}^{-1}$) and yield (higher than 0.45 g g^{-1} at optimal conditions) [68]. The main drawback is that it only ferments hexose sugars (i.e., glucose, mannose, and, under certain circumstances, galactose), but is not able to ferment the pentose sugars, xylose and arabinose, which are present in all hemicelluloses, especially in hardwood and agricultural residues (Table 4). There are naturally occurring yeasts (like *Pachysolen tannophilus*, *Pichia stipitis*, and *Candida shehate*) and bacteria (like *Escherichia coli*, *Klebsiella*, *Erwinia*, *Lactobacillus*, *Bacillus*, and *Clostridia*) able to utilize pentoses, but these have other drawbacks (e.g., less tolerance for ethanol and inhibitors, lower fermentation rate, and a need for rigorously controlled aeration), which make them less suitable for industrial applications [69, 70].

A lot of effort has been devoted to the development of efficient xylose-fermenting microorganisms [71, 72], as xylose is by far the most abundant pentose sugar, but there is also research going on to develop the arabinose fermentation [73, 74] as well as on genetically modified *S. cerevisiae* [12, 75, 76].

Genetic modification of *S. cerevisiae* has got a lot of attention due to the attractive properties of this yeast and its abundant use in industry. *S. cerevisiae* can naturally ferment xylulose; so in order to make it also ferment xylose, a pathway for conversion of xylose to xylulose has to be introduced. This can be done in two ways: either by introducing genes encoding for xylose isomerase (XI) from bacteria and fungi [77–79], which converts xylose to xylulose in one step, or by introducing genes encoding for xylose reductase (XR) and xylitol dehydrogenase (XDH) from fungi [80, 81], which first reduces xylose to xylitol and then xylitol is oxidized to xylulose.

Also, the endogenous XKS1 gene encoding xylulokinase (XK) has to be overexpressed to obtain significant xylose fermentation [81].

The uptake of xylose in *S. cerevisiae* is performed by glucose transporters, which have about two orders of magnitude lower affinity for xylose than for glucose [70] resulting in competitive inhibition of xylose

uptake by glucose. A lot of research has been carried out on transport proteins and introduction of various sugar transporters to increase the uptake of xylose [82]. The presence of a small amount of glucose increases the xylose uptake [83]. This has also been shown in recent SSF studies, with co-fermentation of xylose and glucose, where a slow release of glucose, thus maintaining it at low concentration resulted in increased uptake and utilization of xylose [84–86].

Another challenge in fermentation of lignocellulosic hydrolysates is the presence of various compounds present in the hydrolysate that are inhibiting to the microorganism. These compounds comprise degradation products formed during pretreatment (like furfural, HMF, formic acid and levulinic acid, and phenolics) as well as compounds present in the biomass (like acetic acid and extractives) [87]. The concentrations of these and all other inhibitory substances in the fermentation step depend on the configuration of the preceding process steps.

The inhibitory effect can be overcome by detoxification of the hydrolysate before fermentation. There have been many chemical and physical methods proposed that reduce the concentration of inhibitors and improve the performance in the fermentation step.

Treatment with $\text{Ca}(\text{OH})_2$ (so-called overliming), ion-exchange treatment, and steam stripping may increase the fermentability significantly but may also result in some sugar loss [88, 89]. This will also increase both the capital and running costs.

Another approach is to make the yeast more tolerant, by adaptation to the hydrolysate, and to design the fermentation procedure so that the concentrations of inhibitors are kept at a low level. Cultivation of *S. cerevisiae*, both natural strains and genetically modified strains capable of fermenting xylose, on hydrolysates of steam-pretreated spruce containing inhibitors have resulted in higher ethanol yield and productivity from the same hydrolysate than cultivation on pure sugars [90, 91]. The other approach is to run the fermentation in a fed-batch mode and feeding the hydrolysate at a rate that makes it possible for the yeast to detoxify the hydrolysate in situ [92]. Detoxification occurs when carbonyl compounds – like in furans and phenolics – are reduced to the corresponding alcohols, which are less inhibitory to yeast [93]. In such cases, the fermentation productivity

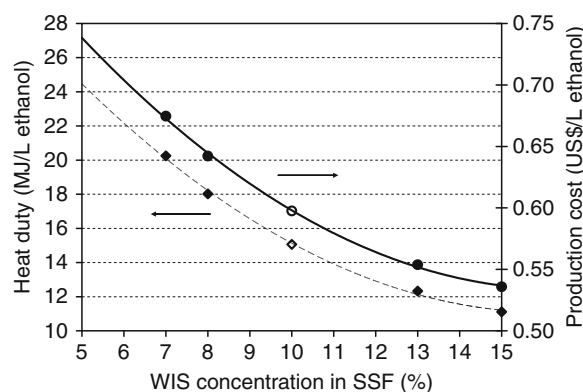
will be a function of the inhibitor concentration, the conversion capacity of the yeast, and the quality of the process control.

One inhibitor usually present in hydrolysates is acetic acid, formed from the acetyl groups present in most hemicelluloses. Acetic acid has a pK_a of 4.75, which is close to the pH of fermentation and therefore a significant amount is in undissociated form that can diffuse through the plasma membrane, and may dissociate inside the cell. This has an intense inhibitory effect on growth of *Saccharomyces cerevisiae*, but leads to an increased ethanol yield at low concentrations, up to 6 g/L [31, 94]. In order to avoid the drop in intracellular pH, the cell must pump out protons using the plasma membrane ATPase. To achieve this, the cells have to produce more ATP, which in anaerobic conditions is done by producing more ethanol and thus resulting in increased ethanol yield [30]. Increased ethanol yield has also been noted in the presence of furfural at low concentrations [95]. At higher concentrations of acetic acid (above 10 g/L), the ethanol yield is decreased while initial furfural concentrations below 5 g/L can be acceptable for fermentation; however, at higher concentrations severe inhibition may occur, which reduces the ethanol productivity [96].

Another option to run the fermentation is by continuous fermentation with several fermentors in cascade. In continuous fermentation, the yeast is retained in the fermentor either by running at a dilution rate below the growth rate of the yeast or by recycling the yeast. This would be beneficial as the yeast gets adapted to the inhibitors present in the hydrolysate. Furthermore, it results in reduced labor costs and reduced fermentor downtime for cleaning and filling, as well as in higher volumetric productivity (in case cells are recycled) compared with batch fermentation [97].

Process Intensification

One of the most crucial factors in process intensification of the ethanol production process is to run the process at as high dry-matter concentration as possible, which leads to decreased size of equipment as well as to reduced energy demands. This leads to less material being handled and less water to be removed in the downstream processing, which has a significant effect on capital and running cost [98, 99]. Figure 7 shows



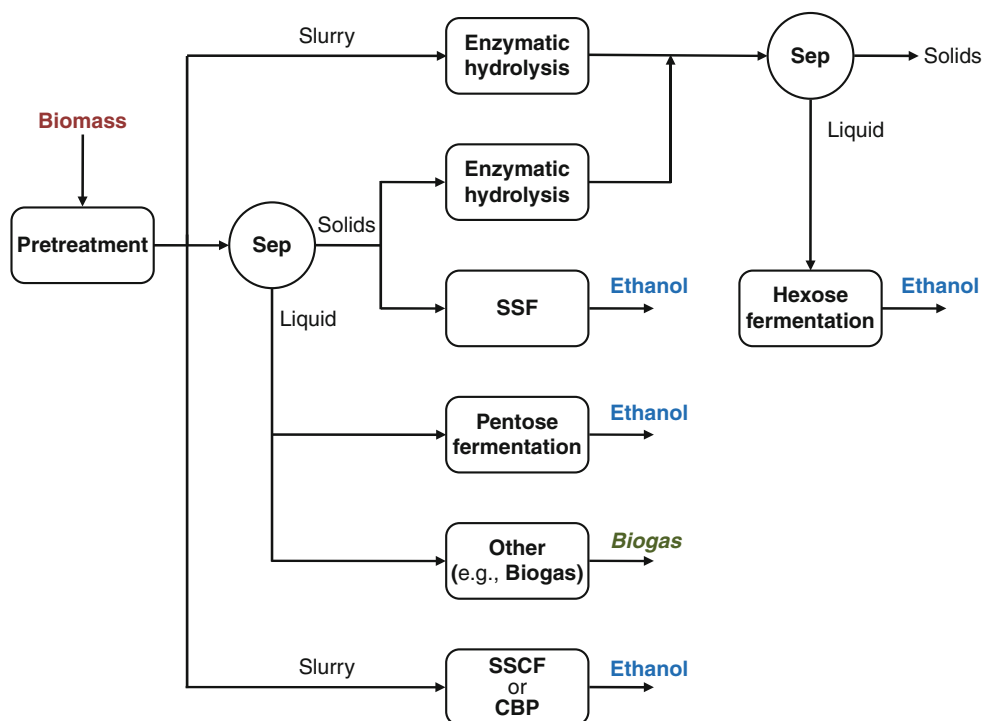
Bioethanol from Celluloses. Figure 7

Comparison of the overall energy demand and total production cost as function of the solid concentration

a comparison of the overall energy demand and total production cost as function of the solid concentration in the SSF for ethanol production from spruce [100] assuming that an increase in dry matter does not affect the conversion yield. Similar relationships were found for corn stover and salix [101, 102].

However, high dry matter leads to problems related to heat and mass transfer in the conversion steps (i.e., pretreatment, enzymatic hydrolysis, and fermentation (or SSF)) as well as higher concentration of inhibitors in the biological steps, as is outlined below. The concentrations of various inhibitors depend though on how the process is designed as can be seen in Fig. 8. In process configurations where the liquid after pretreatment is separated and used for other purposes, the effect of inhibitors on SHF or SSF of the solids diminishes (e.g., IBUS process [103]). The liquid could then be used for other applications (e.g., biogas production) where it may be diluted without negative effects as the product is recovered from a gas phase, where the product concentration is not affected by the substrate concentration in the liquid. Lower inhibitor concentrations can also be achieved by using pretreatment methods that do not create degradation products keeping in mind that several inhibitors, like acetic acid and extractives, are present in the lignocellulosic material and are difficult to avoid.

Another important way to reduce the energy demand in the process and reduce capital cost is by process integration, that is, by using as few process steps as possible. Simultaneous saccharification and



Bioethanol from Celluloses. Figure 8

Various process configurations and some potential products

fermentation (Fig. 8) can be seen as one type of integration that results in both lower energy demand and lower capital cost. SSF has been widely used also for industrial starch-based fuel-ethanol production. By performing the enzymatic hydrolysis and fermentation in the same reactor, the sugars formed by enzymatic hydrolysis are converted by the yeast as soon as they are released. This maintains a low concentration of sugars in the broth which alleviates the end-product inhibition of the cellulases and also diminishes the risk for infections. Another advantage is the capability of the yeast to partly detoxify the slurry [55]. These two effects result in an increased enzymatic hydrolysis productivity compared with enzymatic hydrolysis performed at higher temperatures. This results in higher overall ethanol productivity, which means a lower total reactor volume. It has also been shown in several studies that the ethanol yield is higher after SSF than after SHF both for softwood and agricultural residues [104, 105]. However, the development of new cellulases that are less end-product-inhibited may change this situation in the future.

Another advantage of SSF is that glucose does not need to be separated from the lignin fraction following a separate enzymatic hydrolysis step, thereby avoiding not only a potential loss of sugar but also excessive washing, which dilutes the sugar stream. After the SSF, the slurry is taken to a distillation step where ethanol is distilled off, with negligible loss of ethanol in the remaining stillage stream, and the lignin is then separated by filtration.

The main drawback with SSF is that the yeast after SSF is difficult to recover as it is mixed with the residual solid (i.e., mainly lignin) and also that the optimal temperature and pH for enzymatic hydrolysis and fermentation differ. In spite of this, SSF is in many studies considered as a better option than SHF for several raw materials investigated. The use of SSF is also cost effective, since it reduces the number of reactors [106].

Other studies on SSF have aimed at decreasing the enzyme and yeast concentrations and varying temperature and pH. The enzymes are either produced on-site, which results in less substrate available for ethanol production and thereby a lower overall ethanol yield, or

purchased and thereby add to the cost of chemicals. The yeast will most probably be cultivated using the hydrolysates after pretreatment, in order to adapt it to the hydrolysates. A higher yeast concentration will thus lead to a lower overall ethanol yield. As the rate of the enzymatic hydrolysis is rate-limiting in most SSF experiments, the yeast concentration can be lowered [8, 101, 107] but should not be too low to avoid a stuck fermentation.

When both pentoses and hexoses are fermented together in SSF, the process is referred to as SSCF (i.e., simultaneous saccharification and co-fermentation). In this case, the whole slurry from pretreatment is fed directly to SSF, which reduces the number of process steps compared to separate pentose fermentation and SSF. SSCF can also lead to better utilization of sugars. Studies [84, 85, 108] have shown that the utilization of xylose, using pentose-fermenting yeast, was improved when SSF was used for slow release of glucose, which facilitated the uptake of xylose, compared with when all glucose is available from the start, which is the case in traditional SHF. The slow release may be controlled either by the enzyme dosage, by the temperature during SSF, or by a combination of both [108]. However, it may be difficult to control the slow release of glucose in full scale, so it will be necessary to perform tests in pilot-plant size to evaluate the concept.

Still another option for an even more integrated process is to perform enzyme production, enzymatic hydrolysis, and fermentation in a single reactor, so-called consolidated bioprocessing (CBP) [109]. CBP has the potential for lower bioethanol production costs due to simpler feedstock processing, lower energy inputs, and lower capital cost than separate hydrolysis and fermentation processes. However, this requires a microorganism that produces all the required enzymes and ferments all sugars. This could either be done by engineering bacteria that naturally utilizes cellulose, like *Clostridium cellulolyticum* or *Clostridium thermocellum*, and improve the ethanol production in those or to genetically modify naturally good ethanol-fermenting microorganisms (like the yeast *S. cerevisiae*) to express heterologous cellulase systems. Both approaches have been investigated but to date no microorganisms are available, which are sufficiently effective and the concept is subject to further research.

To avoid problems with mass transfer in enzymatic hydrolysis, SSF, SSCE, or CBP, a short prehydrolysis can be performed where the material is partly liquefied and the viscosity drops. This may be performed in specially designed reactors. One example [110] has been capable of liquefying pretreated wheat straw at solids concentrations up to 40% (w/w) by the use of enzymes. Another way of handling both the mass transfer and inhibitor problems in the biological conversion step, like SSF, is to run in a fed-batch mode.

In recent years, significant progress has been made in running SSF at higher solids loading both by using adaptation of yeast or fed-batch procedures to overcome the effect of inhibitors. Final ethanol yields higher than 70% of theoretical, based on total hexoses and pentoses, and final ethanol concentrations around 4% (wt/wt) can be expected [108].

In case the liquid after pretreatment is removed before the SSF step, that is, using only the cellulose for ethanol production, while the hydrolysate containing the hemicellulose sugars and the inhibitory compounds are used for other purposes (like biogas), the ethanol concentration in SSF can be even higher. An ethanol concentration higher than 6 wt-% has been demonstrated in a combined prehydrolysis and SSF of pretreated wheat straw although the running time was higher than 200 h [103].

The most obvious way to reduce energy demand is by heat integration of steam-requiring process steps. By running the various process steps at different pressures, it is possible to use the secondary steam obtained from the equipment run at high pressure to heat an equipment run at low pressure. This could include integration of the distillation step with the evaporation plant, increasing the amount of distillation columns, or increasing the number of units in the multiple-effect evaporation unit [111]. A somewhat different concept is to introduce mechanical vapor recompression in distillation and/or evaporation [111].

Another option is to replace energy-demanding process units with a less energy-demanding process step. One option that has been proposed to take care of the stillage stream is to evaporate it and concentrate the nonvolatiles to dry-matter content above 50–60 wt-% and then burn the residue in a boiler to produce heat for the ethanol process. Evaporation of the stillage is very energy demanding [100] and is performed mainly

as a wastewater treatment step. The energy obtained from combustion of the concentrated stillage stream is in the same order as the energy needed to perform the evaporation. One option could be to replace evaporation with anaerobic fermentation of the stillage stream for production of biogas. In this way, the energy demand for evaporation can be eliminated and also the capital cost. Both volatile and nonvolatile organic compounds are converted to biogas, which can then be used in the boiler for production of heat and power to the process. Alternatively, the biogas can be upgraded to pure methane to be used as transportation fuel. The amount of biogas that can be produced depends on the composition of the stillage stream and has to be verified experimentally for each specific stillage stream to assure that most of the organics are fermented. Also, the requirement of an aerobic treatment step for final wastewater handling needs to be evaluated. In a couple of studies where evaporation has been replaced by anaerobic digestion, it has been shown that the potential for reducing the energy demand and the ethanol production cost is substantial [112, 113].

External Process Integration

One approach to reduce the production cost for cellulosic ethanol production is to integrate it with another suitable plant (e.g., a combined heat and power plant, a starch-based ethanol plant, a sugar-based ethanol plant, or a pulp and paper mill). The type of plant to integrate with is very much dependent on the biomass that is to be used, the location, and also the process configuration. For instance, in case wood residues are used, it could be suitable to integrate with a CHP plant that is also using forest residues for heat and power production. Part of the solid residue can then be replaced by the lignin fraction available from the cellulosic ethanol plant and the CHP plant provides the ethanol plant with steam and electricity.

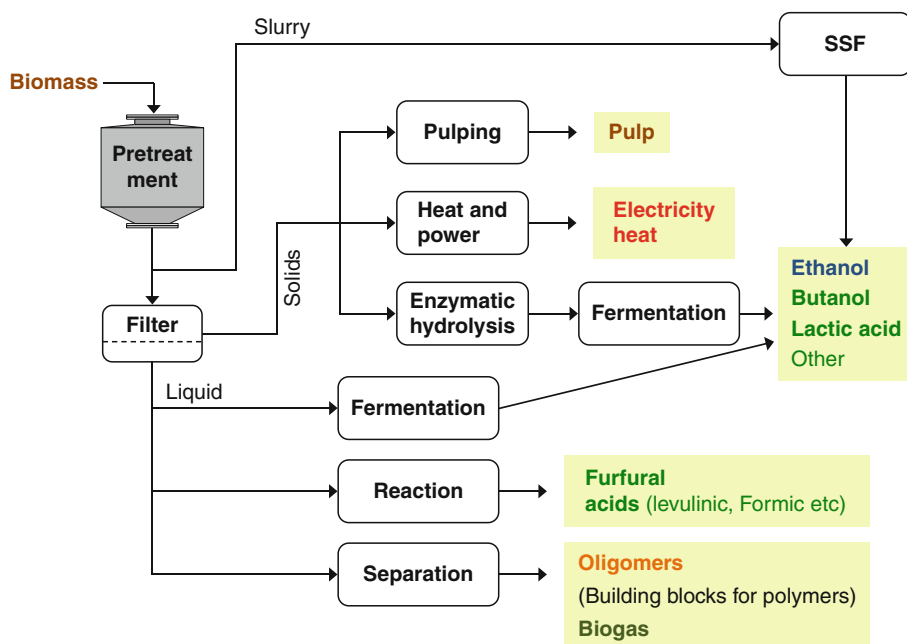
Another option is to integrate cellulosic ethanol production with starch-based ethanol production (e.g., from corn or wheat) to utilize the whole agricultural crop. One benefit is that the raw material is close to the factory and another is that the lignin from the cellulosic part of the material can provide heat and electricity for both processes, that is, both for the first-generation and the second-generation ethanol

plant. Depending on how the integration is performed, it could also help to boost the ethanol concentration resulting from the lignocellulosic process, for example, if the same distillation unit is used for both plants. This will reduce the energy demands in the distillation and the evaporation steps. However, in case the residue from the first-generation plant is to be used as animal feed (DDGS), the integration approach must be carefully chosen to avoid affecting the value of the DDGS. In case the residue is used for biogas production, the integration is easier to implement.

A third option is integration with a sugar-based ethanol production plant (e.g., sugarcane-based ethanol production). The same benefits as for integration with starch-based ethanol production can be achieved.

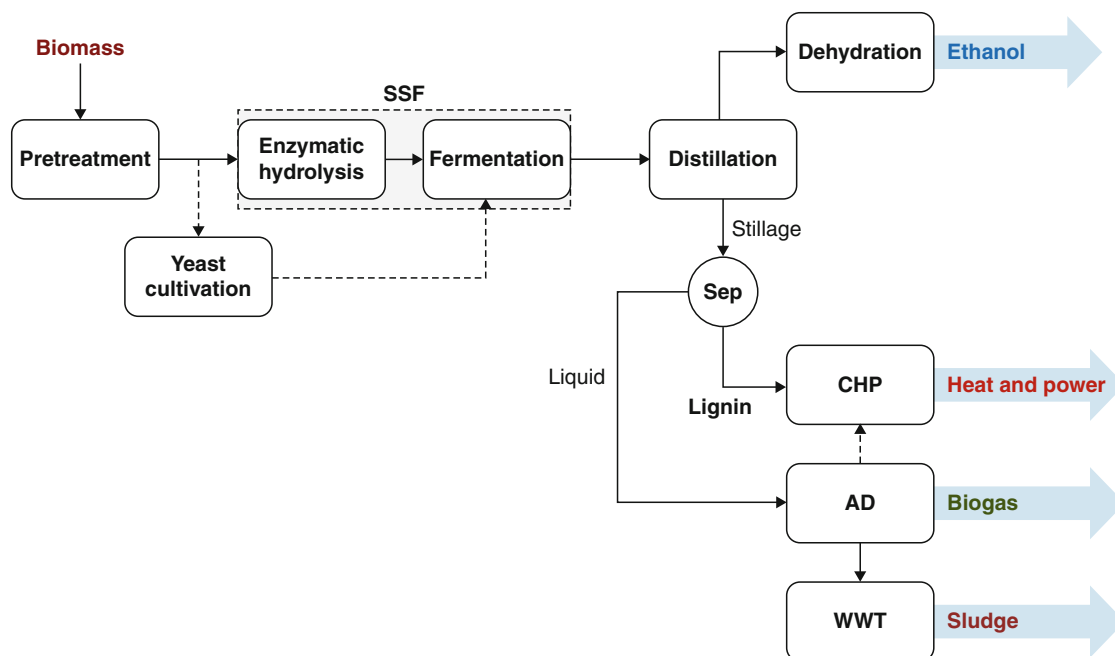
The biorefinery concept, that is, to use the whole crop for production of a variety of chemicals and fuels using chemical and biological transformations, is also an interesting option. Figure 9 shows a variety of products that could be produced when ethanol is produced from either the cellulose fraction only or from both cellulose and hemicellulose. In this case, the income from other products improves the overall process economics.

Integration with Heat and Power Plant Integration of cellulose-based ethanol production with a combined heat and power plant (Fig. 10) has the possibility to reduce the production cost of ethanol. One of the benefits is that the syrup or lignin residue can be used for steam production without prior drying, which reduces the energy demand. This type of integration is even more interesting in case the plants are combined with district heating as the heat of condensation in the flue gases from the CHP can be utilized for district heating. Also the excess heat from the ethanol plant can be utilized for this purpose. Such integration has been shown to increase the energy efficiency and reduce the production cost by up to 20% for conditions prevailing in Sweden [114]. The study was based on ethanol production from 200,000 t of spruce per year. Various options for the utilization of the solid residue formed during ethanol production from spruce, such as the production of pellets, electricity, and heat for district heating, were compared. The overall energy efficiency ranged from 53% to 92% (based on the lower heating values, LHV) with the highest value for



Bioethanol from Celluloses. Figure 9

A selected number of potential products from biomass



Bioethanol from Celluloses. Figure 10

Integration of a cellulose-based ethanol production with a combined heat and power plant

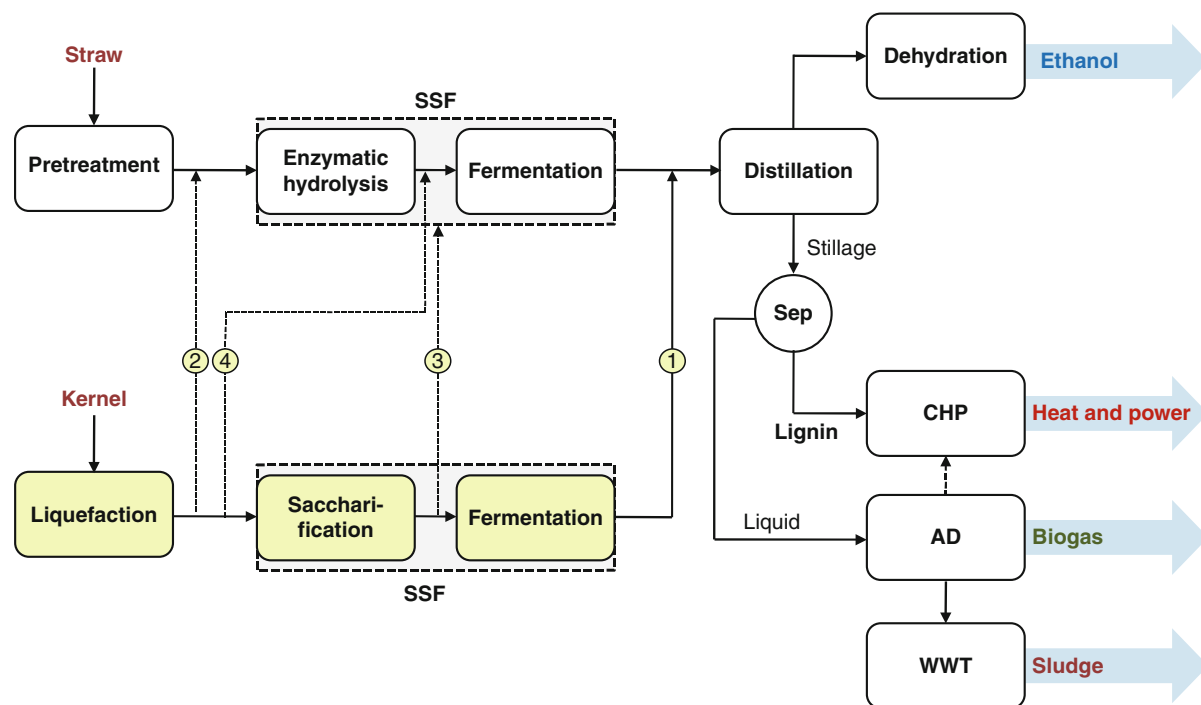
cases with district heating, where a large part of the low temperature waste heat from the process can be utilized. However, this option restricts the location to the vicinity of larger cities of the plant as there must be a demand for the surplus heat. Similar conclusions regarding utilization of waste heat were reached in a study on coproduction of ethanol and electricity from softwood, based on conditions in California [115].

In a recent study on ethanol from spruce [113] several configurations where evaporation of the liquid fraction of the stillage stream from distillation was replaced by anaerobic digestion (AD) followed by aerobic wastewater treatment were investigated. In the best case, the energy efficiency, based on LHV, for the combined production of ethanol and biogas was 59% and the overall efficiency, including the contributions from electricity and district heat, was 92%. This process configuration resulted also in the lowest ethanol production cost. The total ethanol production cost was diminished by 17–22% compared with the base case using evaporation of the stillage stream and burning of the concentrated syrup in the CHP.

Most of the existing pilot and demo scale plants for cellulosic ethanol production are integrated with production of power and steam, mostly using the lignin fraction.

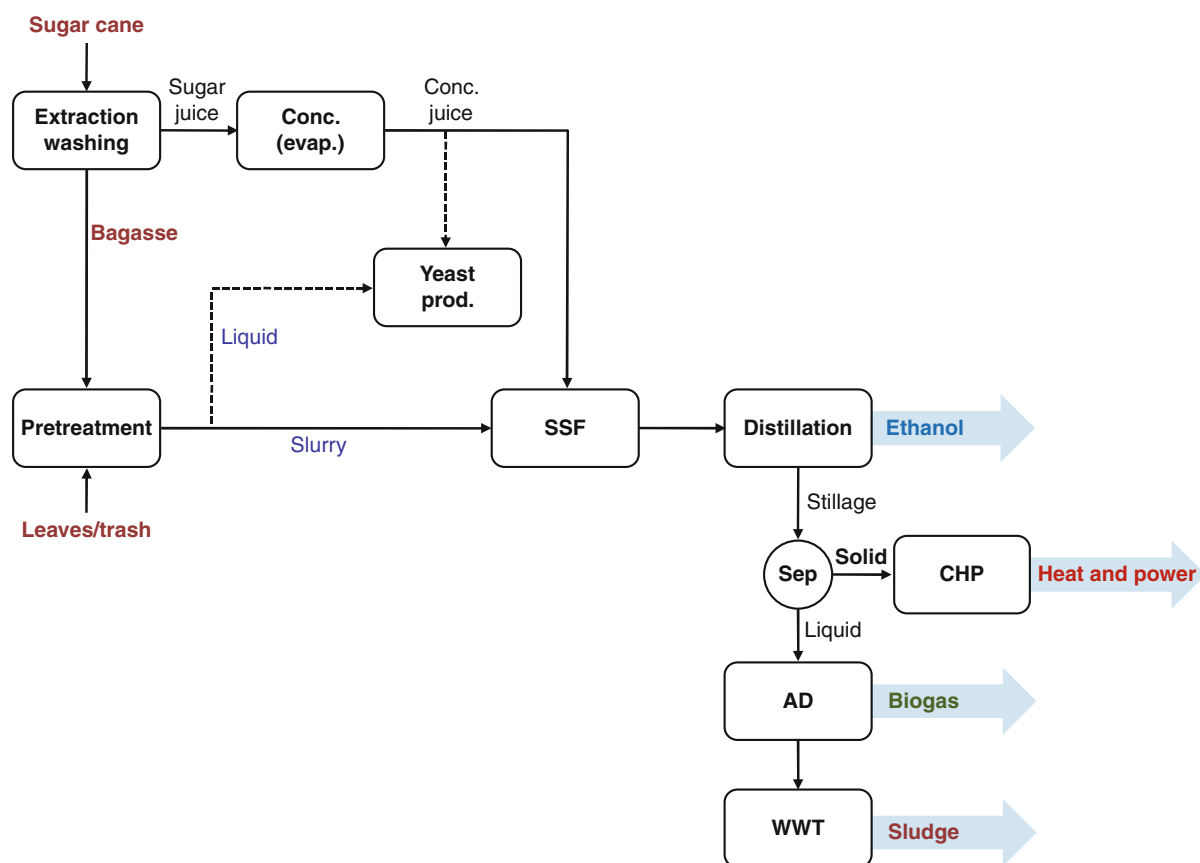
Integration with First-Generation Ethanol Another option is to integrate second-generation cellulosic ethanol production with first-generation starch-based or sugar-based ethanol production to use the whole agricultural crop (Figs. 11 and 12, respectively). Suitable residues are corn stover, corn cobs, corn fiber, wheat straw, and sugarcane bagasse and leaves/trash. There are many possible ways to integrate the processes (Fig. 11) for the starch-based case, and the desired choice of integration is very much influenced by the choice of coproducts.

The absolute lowest degree of integration is to share the heat and power production plant where the lignin residue, and in some cases also biogas, from the second-generation plant is used to provide heat and electricity to both plants. This is perhaps the most obvious integration in corn-based ethanol plants in the USA where the corn is used to produce several different



Bioethanol from Celluloses. Figure 11

Integration of starch-based and lignocellulose-based ethanol production



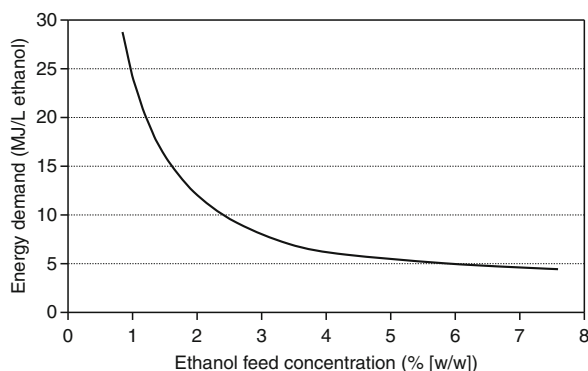
Bioethanol from Celluloses. Figure 12

Integration of sugarcane-based and lignocellulose-based ethanol production

coproducts, besides ethanol, and where most of the plants are using natural gas for heat and power production. In case this is replaced by heat and power from the cellulosic material, it will improve the sustainability of these plants. Another option, at a low integration level is to use a combined distillation plant (option 1 in Fig. 11). The two processes would have separate and dedicated equipment for pretreatment, hydrolysis and fermentation. As it is usually difficult to reach high sugar and ethanol concentrations in the second-generation ethanol production, while starch- or molasses-based ethanol production require dilution of the sugar, the latter could be used to boost the second-generation ethanol stream to reach ethanol concentrations well above 4–5 wt-%. This would result in a decrease of the critical energy demand in the combined distillation

step compared with distillation in two units well below 4 wt-% ethanol (Fig. 13).

The possibility for integration in the upstream direction increases when both first- and second-generation plants are designed and erected simultaneously. Figure 11 shows some options [2–4] where material streams are combined further upstream. This could reduce not only the equipment cost but also the energy demand. Integration may also alleviate some of the inhibitory effects occurring from formation of toxic compounds in the pretreatment step. If the process streams are mixed prior to fermentation the lignocellulosic streams will be diluted by the starch- or sugar-based streams. The integration may in some cases also lead to higher ethanol yield from the first-generation plant. In a study where pretreated wheat straw was



Bioethanol from Celluloses. Figure 13

Energy demand in the distillation step, where ethanol is concentrated to 94 wt-%, as a function of the ethanol feed concentration. The step was assumed to consist of two stripper columns (25 trays each) and a rectification column (35 trays) heat integrated by operating at different pressures. The inlet feed temperature was increased from 80°C to the boiling temperature before entering each stripper column

mixed with wheat starch, a higher ethanol yield as compared with using either only starch or only wheat straw was obtained using SSF [116]. This was probably due to the stress on *S. Cerevisiae* caused by weak organic acids present in the hydrolysate of steam-pretreated wheat straw. It is also easier to reach a high ethanol concentration using such a mixture than when using wheat straw only as a raw material. The use of the wheat starch, coming from wheat flour, is rather rich in nutrients, which could also contribute to decrease the amount of additional nutrients needed in SSF of wheat straw.

Figure 12 shows a fully integrated ethanol production process for utilization of the whole sugarcane plant. In this case, the sugarcane bagasse (i.e., the residue of the cane after extraction of sucrose) is already on site at the ethanol mill. In many sugarcane ethanol plants, the bagasse is used to provide steam for the process and to cogenerate electricity, but by using a part of it for ethanol production the value chain can be increased [117]. Another option is to also use the leaves of the sugarcane, which in many cases today are burnt on the field creating an air pollution problem. In Brazil, which is a large producer of sugarcane ethanol, the government is becoming more restrictive regarding

burning of residue in the field [118]. The development of more efficient burners [119–121] will also allow more effective use of these resources.

To summarize, the integration of first- and second-generation bioethanol production results in higher ethanol yield, lower energy demand, and lower production cost than by using a stand-alone second-generation ethanol production. To define the most optimal way of integration requires detailed studies (e.g., by flow-sheeting calculations based on reliable experimental data).

Future Directions

Substantial progress has been achieved in the field of lignocellulosic fuel-ethanol production and several pilot and demo plants have been built the recent years [122]. However, there are still several challenges remaining before reaching a mature industrial technology. Some of the most important challenges are:

- To produce ethanol at a high concentration. The most obvious is to perform enzymatic hydrolysis or SSF at high dry-matter concentration. This requires improvement of enzymatic hydrolysis with efficient enzymes, reduced enzyme production cost, and novel technology for high solids handling. Another important factor is to utilize all the sugars available in the pretreated material, that is, either including pentose fermentation or to produce some other energy product like biogas. The former will lead both to a higher ethanol concentration and to a lower production cost, while the latter results in a facilitated ethanol production from hexoses.
- The increase in concentration of inhibitory compounds with increased dry matter may lead to a decreased ethanol yield. To cope with this, an option is to separate the solid and liquid fractions and only use the solid fraction (i.e., the cellulose) for ethanol production. The liquid could then be used for other applications (e.g., biogas production) where it may be diluted without negative effects in the product recovery as the biogas is obtained in the gas phase.
- Development of robust fermenting organisms, which are more tolerant to inhibitors and ferment both pentoses and hexoses in the raw material in concentrated hydrolysates with high yield, at high

productivity and with high ethanol concentration. The co-fermentation of pentoses and hexoses will lead both to a higher ethanol concentration and to a lower production cost.

- Extension of process integration to reduce the number of process steps and the energy demand and to reuse process streams to eliminate the use of fresh-water and to reduce the amount of waste streams.
- Process integration with other types of industrial processes, for example, a combined heat and power plant or first-generation ethanol plant, which will reduce the production cost further. This may result in higher ethanol concentrations to the distillation step compared with a stand-alone second-generation plant.

One of the most important issues is to verify all process steps in an integrated way in pilot and/or demo scale. These plants should provide data for full-scale ethanol production and at the same time define new challenges for further research. The step from pilot- and demo-scale production of lignocellulosic ethanol to competitive full-scale production requires further reduction of the production cost. In pilot and demo scale, it is important to prove the whole process for longer periods of time with variation in raw material, which can be due to normal variations in crops due to where it is grown and the climate as well as by changes during storage. High accessibility and verification of yields and productivities obtained in lab and bench scale has also to be achieved, especially for critical process steps as pretreatment and SHF or SSF. Also more technical issues like separation of lignin and the influence of process integration and recycling of process streams on fouling. The qualities of products and coproducts as well as wastewater treatment are other important factors.

A conclusion to be drawn is that there is a significant potential of improvement and development. The production processes can be far more efficiently designed in the future as compared with prevailing concepts considering individual process steps, process configurations, and a huge number of combinations of process integration options.

This complexity and large number of design options could be considered both as positive and negative features when it comes to industrial implementation. The positive side is that the production process

can be optimized for the specific local conditions, depending on available raw materials, heat sinks for use of district heating, demand for biogas as vehicle fuel, and other existing facilities to integrate with. The ethanol production system can then be designed to optimize the overall energy efficiency and profitability for the entire system. The negative side is that the high complexity requires a huge amount of knowledge for development of the most optimal production systems, which is not yet available.

To conclude, lignocellulosic ethanol has a promising role to play in the development of efficient and sustainable biofuel production systems in the future, but this requires improved knowledge and competence among all the different actors involved in this process. Furthermore, a more integrated work is needed between different research fields, such as process development and configuration and energy and environmental systems analysis (e.g., life cycle assessments) to optimize future production systems in a most efficient way regarding an economic, energy efficient and environmental sound perspective.

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Bioethanol from Starch

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Article Outline

Glossary
 Definition of the Subject and Its Importance
 Introduction
 State of the Art of the Production
 Actual Status
 Future Directions
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Glossary

Alcohol Often used trivial name for ethanol, in chemistry it describes the class of alcohols including also methanol, butanol, etc.

Bioethanol Product of a fermentative process used mainly as a fuel from renewable substrates in comparison to the use of fossil fuels.

Ethanol Chemical name of an alcohol with the molecular formula $\text{CH}_3\text{—CH}_2\text{—OH}$ and is the same chemical substance as bioethanol and has other synonyms like bioethanol, ethyl alcohol, pure alcohol, or drinking alcohol.

DDGS Animal feed called “distillers’ dried grain with solubles.”

Fermentation Process step which produces ethanol and CO_2 as product.

Liquefaction Enzymatic process step using amylases to cut the starch chains into oligosaccharides.

Saccharification Enzymatic process step using beta-amylases and glucoamylases to cut oligosaccharides into fermentable sugars.

Starch Starch is a very important part of the human food in sources like wheat, maize, rice, potatoes, and many other plants and is also a source of sugars for the fermentation.

Thin stillage Liquid stream received from the decanter containing dissolved nutrients and salts.

Yeast *Saccharomyces cerevisiae* is the organism used in the ethanol production industry.

Wet cake Solid-rich stream received from the decanter containing nutrients like proteins.

Definition of the Subject and Its Importance

Ethanol is a very interesting chemical compound which can be used in different applications such as drinking alcohol in beverages as well as in chemicals, pharmaceuticals, and biofuels. Production of alcoholic beverages based on biomass containing sugar can be assumed as old as human civilization. The production of ethanol from starch using a fermentation process started most probably in beer-producing countries approximately in the twelfth century. The production of “pure” ethanol is also a very long known process. The development of more efficient distillation processes in the nineteenth century led to large increase in industrial trade of ethanol. The largest amount of the industrial ethanol was still used for alcoholic beverages. But also other applications like the use in the chemical industry, as lamp fuel and as a fuel have been exploited.

The use of ethanol as a fuel started at the beginning of the twentieth century, the time the Ford Model T could run since 1908 on ethanol. With the fast development of the petroleum industry, the use of ethanol as a fuel was negligible till late twentieth century. Due to price increases of raw oil and also environmental concerns, ethanol showed a revival as a fuel based on renewable substrates like sugar and starch or even celluloses. For fuel applications, mainly the name bioethanol is used but the whole ethanol production chain including also the agricultural growth of the substrate has to be taken into account to prove that the produced ethanol really shows significant environmental benefits compared to fossil fuels.

This entry concentrates on bioethanol from starch only. Bioethanol from other substrates like sugar and lignocellulosic material will be discussed in the respective entries. Bioethanol from starch reached 2009 a share of about 60% of the total worldwide production. Starch as a substrate is mainly used in the USA and Europe. Since the worldwide need for transportation fuels is steadily increasing, there is a need for a further increased production of sustainable produced biofuels like bioethanol. Since starchy substrates are also the basis for human nutrition and animal feeding, it is very important to balance the use of these very valuable materials. A large amount of the worldwide produced grain crops are used for animal feeding. Using these grain crops for bioethanol production, about the same amount of animal feed is produced as a very important second product. This allows a combination of animal feed production with bioethanol production and is already installed in many bioethanol-producing plants worldwide which use grain crops as substrate. Taking this fact into account, it will be possible to increase the bioethanol production based on grain crops further to a certain extent keeping the whole system of bioethanol production combined with human nutrition and animal feeding into account. Further significant increase in bioethanol production will be achieved if combinations of starch and lignocellulosic substrates or lignocellulosic substrates only are fully economically developed. Details on lignocellulosic substrates for bioethanol production can be found in the respective entries.

Introduction

Production of bioethanol from starch is, in addition to the production from sugar, also a very well-known process. The technology and process steps needed for starchy materials differ compared to sugar-containing substrates in the substrate treatment section of the bioethanol plant and in the stillage treatment processes (Fig. 1). After milling of the starchy substrates two enzymatic process steps, the liquefaction and the saccharification, are needed to receive a fermentable sugar solution. The fermentation of this sugar stream can be done traditionally using yeast. The further downstream process steps are distillation and rectification of the liquid stream to increase the concentration of the bioethanol. The final product quality in terms of allowed water content in the bioethanol is reached normally by using an adsorption process. The stillage received from the distillation or beer column is further treated in a decanter to separate a wet cake stream and a thin stillage stream which can partly be recycled to mash preparation or concentrated in an evaporation process. After concentration, the thin stillage is mixed with the wet cake and together tried to produce an

animal feed as a second product the so-called distillers' dried grain with solubles (DDGS).

Currently the world bioethanol production is based approximately to 40% of sugar crops and 60% of grain crops as feedstock. Sugar is mainly used as substrate in Brazil and other sugar-producing countries. Starch as main substrate for the bioethanol production is used in the USA and Europe and also in many other countries. In Europe, also sugar from sugar beet processing like molasses are used to some extend as co-substrate for bioethanol production depending on the price of the substrate.

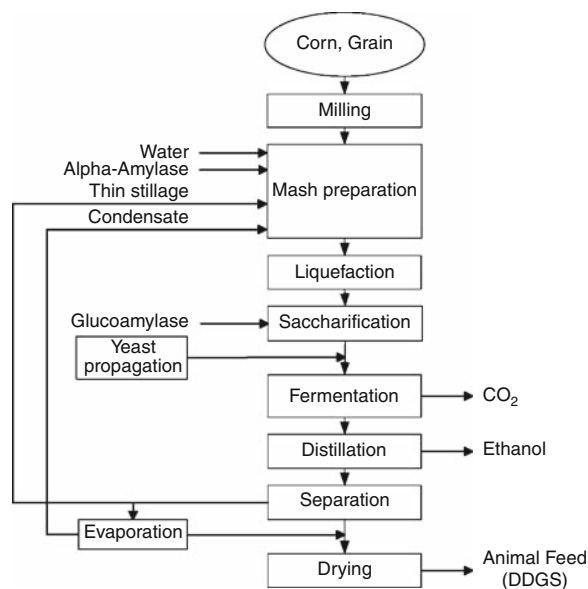
State of the Art of the Production

Raw Materials Containing Starch

Starch is a polysaccharide consisting of a large number of D-glucose molecules which are linked by glycosidic bonds. Green plants can produce D-glucose from carbon dioxide (CO_2) from the atmosphere and water via photosynthesis using sunlight. D-glucose is used from the plant for growing. Access amount can be stored in the plant as starch in the form of granules. Within the stored polysaccharide glucose can be in the linear form via 1,4-alpha glycosidic bonds (amylose) as well as in the branched form via 1,6-alpha glycosidic bonds (amylopectin). In different plants, the starch content of amylose can vary between 20% and 25% and a respective content of amylopectin from 75% to 80% [1]. Within the bioethanol process, mainly the amylopectin content of the starch is responsible for the strong increase of viscosity during the treatment which has to be taken into account in designing the process.

For the bioethanol process, a broad variety of starch-containing plants are used. The choice of feedstock varies a lot in different regions of the world. Within the US Corn Belt, maize (or corn) is the main feedstock. In Europe, Canada, and many other regions wheat, corn, and other cereals like barley, rye, and triticale (a hybrid of wheat and rye) are used for bioethanol production.

Other interesting feedstocks are potatoes, cassava, and sorghum. Potatoes are grown in many countries. The main disadvantage is the high water content (Table 1) which results in high transportation costs



Bioethanol from Starch. Figure 1
Principle of dry-mill bioethanol process

Bioethanol from Starch. Table 1 Feedstock composition

Component	Maize	Wheat	Barley	Rye	Sorghum	Potato	Cassava chips	Cassava roots
Water ^a	12–15	11–14	11–14	11–14	11–14	75	11–14	60–70
Starch ^b	65–72	62–70	52–64	52–65	72–75	60–75	65–82	40–85
Sugar ^b	2.2	–	–	–	–	0.3–5.5	0.25	0.75
Protein ^b	9–12	12–14	10–11	10–15	11–12	6–11	2.3	1.5–3.5
Fat ^b	4.5	3	2.5–3	2–3	3.6	0.5–1.1	0.8	0.2–0.4
Cell wall material ^b	9.6	11.4	14	–	–	–	–	0.6–1
Fiber ^b	–	–	–	–	–	–	4.6	1.6–2.9
Ash ^b	1.5	2	2.3	2	1.7	2.5–5.4	2–5	0.6–1.2

Adapted from [2, 3]

^a% w/w (as-is basis)^b% w/w (dry basis)**Bioethanol from Starch. Table 2** Bioethanol and distillers' dried grain with solubles (DDGS) yield from various starchy feedstock

Yield (kg/t)	Maize	Wheat	Barley	Rye	Sorghum	Potato	Cassava chips
Ethanol (kg/t)	325	299	248	269	328	93	361
Ethanol (l/t)	411	379	314	340	415	117	457
DDGS (kg/t)	321	429	496	457	341	Wet cake	Wet cake

and losses during storing. Cassava with alternative names yucca, tapioca, or manioc is a tropical plant developing starch-containing roots. As a fresh root, it has high water content. Therefore, long-term storage without drying is barely possible. But drying needs separate handling and treatment. In Table 1, the composition of starchy feedstock is listed.

The bioethanol-producing potential from the listed feedstock is given in Table 2 [3]. An average bioethanol yield has been assumed and also the DDGS product yield is listed. For potato and cassava chips, usually the wet cake is further used and not dried.

From Table 2, it can be seen that the highest bioethanol yields from 1 t feedstock (as is basis) is achieved from cassava chips, sorghum, and maize followed by wheat. The yield of animal feed (DDGS) also varies with the substrate used. Substrates giving the lower ethanol yields give higher animal feed yields

like barley, rye, wheat, sorghum followed by maize showing nearly the same yield for bioethanol and animal feed.

Processing of Starch-Containing Raw Materials

To achieve the highest bioethanol amount from the feedstock used, it is important that the optimal conditions are adjusted for the yeast. Hence, it is necessary that sugar and minerals are available in an ideal concentration. Additionally, the temperature and pH need to be kept in the optimal range for the microorganism.

In general, the design and mass balance of bioethanol plant based on corn and wheat is similar and both feedstocks can be used in the same plant if designed properly. Special attention need to be addressed to the fact that in wheat the content of

nonstarch polysaccharides is higher than in corn. Especially the pentosane and glucan are responsible for the increase of viscosity and fouling tendency in the process which leads to reduced heat transfer rates in the heat exchangers. To reduce or avoid problems in the process, special enzymes for reducing the chain length of these substances to make them soluble in the process stream need to be applied. Higher viscosity of the mash need to be controlled by solid concentration which might lead to lower ethanol concentration after the fermentation which results in a higher energy demand of the whole process. Also during processing of wheat the lower lipid concentration combined with higher raw protein content (approximately >13%) leads to an increased foaming tendency during fermentation which might need dosing of antifoaming agents [2]. In Fig. 2, a schematic layout of a dry-mill bioethanol process with DDGS production is shown.

In the following entries, the different process steps are discussed in detail.

Grinding Process The first step in the production of bioethanol from starch is the milling (grinding) of the feedstock. Two different processes are possible: the wet-mill or the dry-mill process.

- In the past, wet-mill processes were often used since several valuable products like corn oil, gluten meal, various starch qualities, and feed products can be derived besides bioethanol which is not the main product during this process [4]. Wet-mill plants are more complex and need approximately 40% more investment than a comparable dry-mill plant because the whole by-product separation equipment must also be installed [5].
- The dry-mill process [6] is optimized for the production of bioethanol and animal feed called distillers' dried grains with solubles (DDGS). The dry-mill process needs less energy per ton of bioethanol produced. Nowadays, most bioethanol for the use of fuel is coming from a dry-mill process. For this process, the corn or grain is ground into coarse flour which is further processed (Fig. 2).

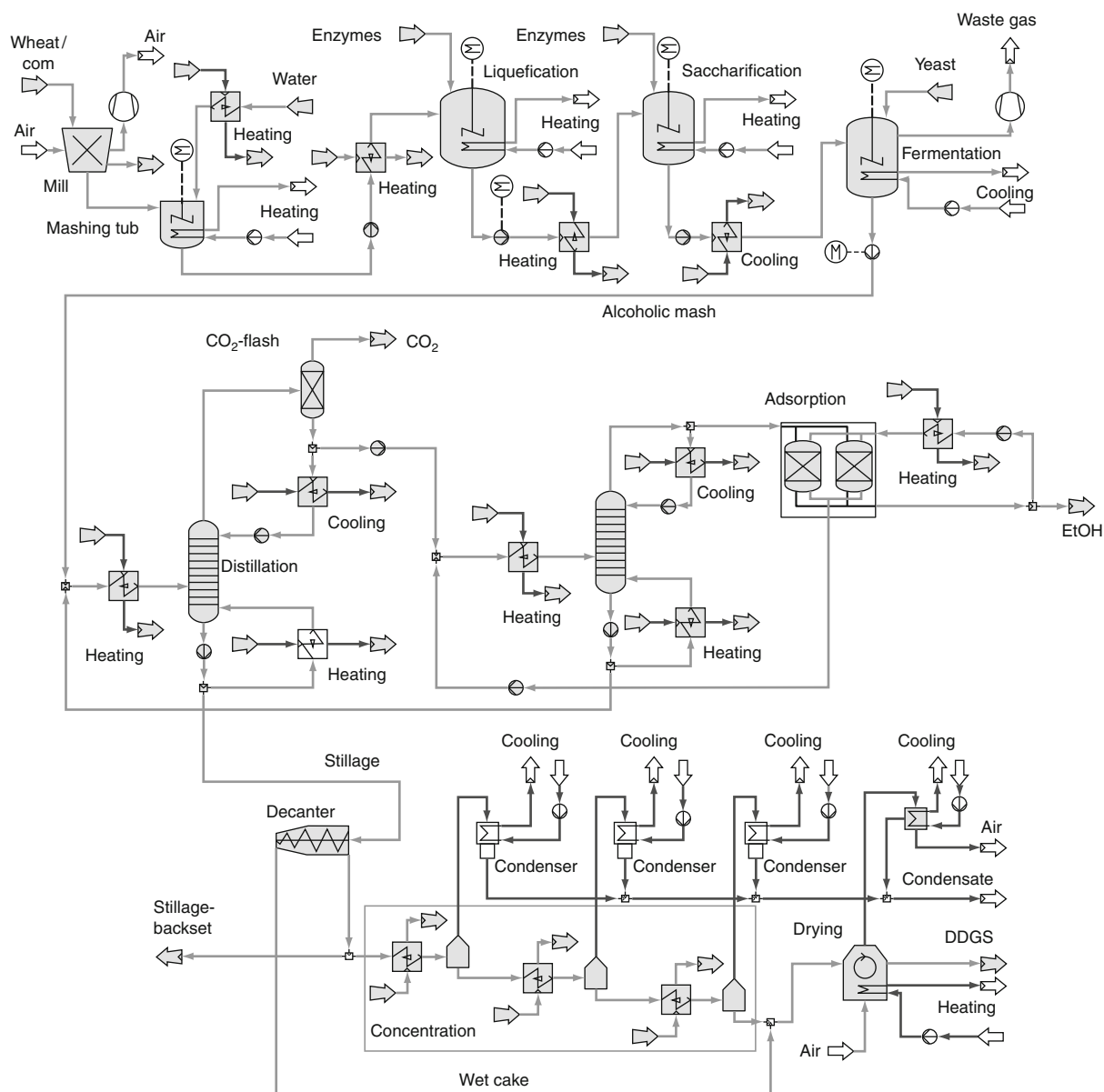
In a standard dry-mill process, the grain is feed by gravity to the mill and grinded usually using a hammer mill. The particle size of the meal has an important

influence on the enzyme effectiveness and also on the ethanol yield. The ground meal is mixed in the mashing tub with water (fresh or recycle streams) and alpha-amylase to prepare the mash as can be seen in Figs. 1 and 2.

Liquefaction Process For the nearly complete use of starch in a technical bioethanol production, an enzymatic process step using amylases is obligatory. Therefore, two different groups of starch-degrading enzymes are needed. Alpha-amylases are responsible for the fast break down of the viscosity of the starch solution by cutting the starch chains into oligosaccharides consisting of seven to ten glucose molecules. This is the so-called liquefaction step. Already in the mixing step during the mash preparation, the liquefying enzymes (alpha-amylase) need to be added to avoid problems due to gelatinization of the starch granules. The resulting mixture is heated and held at this temperature for a certain time. The pH also has to be adjusted according to the needs of the enzymes used.

The temperature ranges for the gelatinization of several cereals are well known (Ingeledew 2009). Depending on the type of cereal and the process strategy, the temperature can be held first below the gelatinization temperature which is usually in the range of 50–60°C for approximately 20 min and then heated up to the final liquefaction temperature which can be in the range of 80–85°C or even up to 105°C depending on the stability of the enzymes used. In another process strategy, the whole mash is heated up quickly to temperatures between 105°C and 120°C in a hydrotreater (jet cooker) unit. Here the temperature is held for approximately 5 min, then the whole mixture is fed to an atmospheric or vacuum flash vessel and from that to the liquefaction vessels where the enzymes are added. Within this process step, the temperature is held at around 80–90°C for about 30–60 min. The pH value can vary between 5.0 and 6.0 or 6.2 and 7.5 depending on the type of enzymes used [7].

If water is present during heating, the starch granules are dissolved which allows the enzymes to break the starch chains fast into smaller parts. This allows avoiding a very strong increase of viscosity and a blocking of the used equipment.



Bioethanol from Starch. Figure 2

Schematic layout of a dry-mill bioethanol process including distillers' dried grain with solubles (DDGS) production

After this liquefaction procedure, the whole mixture is cooled and the saccharification step is performed prior the start of the fermentation.

Saccharification Process As described above in the liquefaction step, the alpha-amylase can only break the 1,4-alpha glycosidic bonds of the starch. The second

enzymatic process step is needed to break down the dextrins into single glucose molecules by beta-amylase and glucoamylase. The latter is an exoenzyme which attacks the oligomers in the solution from the chain ends. Glucoamylase can hydrolyze 1,4-alpha glycosidic bonds as well as 1,6-alpha glycosidic bonds. But the reaction rate is much slower. The result is

a fermentable sugar solution containing glucose and maltose. The glucoamylase used in technical processes has a temperature optimum of 60°C and a pH optimum of 3.4–5.0. This means that this enzyme is stable under fermentation conditions. Due to this fact, it is possible to perform the saccharification in two ways.

- The first option is a separate saccharification vessel where the optimal temperature of the enzyme of 60°C can be adjusted and the fastest enzyme reaction rate can be achieved as it is shown in Fig. 1. This process strategy is also called separate hydrolysis and fermentation (SHF).
- The second option is that the saccharification step is combined with the fermentation to a simultaneous saccharification and fermentation (SSF) procedure. In this case, the temperature is around 33–34°C and the pH is approximately 5.0 resulting in an enzyme activity that is not as high as at the optimum. But since the yeast activity is the time-limiting step, the slow release of sugars is not limiting the process. This approach evermore shows the advantage that the optimal release speed of fermentable sugars keeps the yeast at the best performance rate, optimal temperature and pH assumed, since glucose itself is limiting the yeast at higher concentrations. This is the reason that in modern technical bioethanol plants the SSF approach is mainly used.

Yeast Propagation Before the fermentation process itself takes place, it is necessary to produce the yeast needed. Very often the yeast is grown in the bioethanol plant itself in smaller yeast-growing fermenter to be provided for the ethanol production fermenter. Some yeast can be recycled after ethanol production depending on the substrates used. Additionally, the solid matter content is restricting the yeast recycling. Working with clear streams like during processing of sugar solutions, a high degree of yeast recycle is possible after treatment. With starch as feedstock, yeast recycling is restricted.

The dominant yeast strain used in the ethanol production industry is *Saccharomyces cerevisiae* because it is a very robust organism which also shows a relative high inhibitor tolerance and a very good production capacity. Using this yeast, many plants in the USA

produce ethanol in the range of 20% (v/v) on volume basis which is equal to 16.5% (w/w) on weight basis [8].

Yeast shows the ability that only cell growth can be achieved in an aerobic environment in the presence of sufficient oxygen. Nearly no ethanol production occurs in this situation. This can be used for reproduction and increasing the cell mass as needed.

The commercial yeast production can start from active dry yeast supplied to ethanol production facility by specialized yeast-producing companies. Growing the yeast on site in a separate propagation vessel, it is possible to keep about 10% of concentrated yeast solution to start the next yeast production cycle. To continue this production cycle, it is very important that no bacterial infection occurs which has to be checked thoroughly. For the yeast propagation facility, sterile conditions are crucial. The same substrate as used for the ethanol production can be used for yeast propagation. In this case, the produced yeast is already adapted to the substrate. Only a dilution by a factor of 2 is used to keep the sugar concentration low and this also restricts the production of ethanol during yeast growth. The temperature is kept several degrees lower than during the ethanol fermentation and the propagation vessel is aerated to a sufficient amount avoiding the buildup of excessive foam.

The yeast propagation can be performed in a semicontinuous or in a continuous mode. The method chosen depends also on the performance mode of the ethanol fermentation itself.

Fermentation Process As the starch content in the feedstock cannot be directly converted by yeast cells to bioethanol, it needs to be broken down as described above into usable sugars before fermentation. These sugars can be the glucose itself or the maltose or maltotriose which consist of two or three glucose molecules. The different sugars which can be converted by the yeast *S. cerevisiae* are well known [2]. The resulting sugar solution is called mash. It can be used for fermentation which is started by adding the yeast inoculum.

During the fermentation, one glucose molecule is converted to two molecules of ethanol and two molecules of carbon dioxide. This means that in the ideal case from 1 kg Glucose, 0.511 kg ethanol and 0.489 kg

CO₂ are produced by yeast releasing 867 kJ heat [7]. The fermentation itself can be done in batch or continuous mode. Both systems have advantages and disadvantages.

- The batch fermentation mode is characterized by a discontinuous operation. First the fermentation vessel is cleaned and sterilized and then filled with the already liquefied mash after passing a heat exchanger to adjust it to the proper fermentation temperature below 35°C. Then the fermentation can be started by adding the already prepared yeast solution from the propagation vessel. The pH is adjusted to around 5.2 and kept constant by dosing a basic solution or allowed to decrease during the fermentation till a pH of 4.2. If the pH drops to a value lower than 4.0, most probably an infection with lactobacilli has occurred. During the fermentation period normally in the range of 50–60 h, the temperature has to be kept below 35°C by applying continuous cooling of the fermentation vessel. After finishing the fermentation, the alcoholic mash is pumped to a storage tank (called beer well). Then the cycle can be started again with cleaning and sterilization. Due to this procedure of emptying, cleaning, sterilization, and again filling of the fermentation vessel the effective time is reduced by around 20%. This means only 80% of the reactor volume is active. Therefore, a bigger reactor volume is needed. But since the whole plant requires a low degree on control equipment, low investment costs are resulting [2]. But high yields in the range of 90–95% of the theoretical yield combined with high ethanol concentration can be achieved. The size of the fermentation vessels are in the range of 800–1,500 m³. In Brazil in new plants, the volume of the fermentation vessels is increased up to 3,000 m³ [9].
- In the continuous fermentation mode, a constant stream of mash is fed to the first fermentation vessel. Depending on the feed volume stream and the vessel volume which is also in the range as mentioned above a certain residence time of the mash combined with a defined specific dilution rate is applied. It is very important that the specific dilution rate is below the growth rate of the yeast to keep the microorganism in the fermentation

vessel in the desired concentration range. Along the various fermentation vessels, the sugar is consumed by the yeast and ethanol and new yeast cells are produced during the fermentation. During this process the relevant parameters need to be measured and controlled properly. Additionally, a defined dosage of air is necessary to achieve a high specific production rate of ethanol of around 6 kg/m³ h. This is about more than three times higher as in batch systems with approximately 2 kg/m³ h. However, in the last fermentation vessels the yeast is already under stress due to high ethanol concentration so that cell recycling or fresh yeast addition might be required. In this case productivities of up to 30–50 kg/m³ h are possible [2]. The increased ethanol productivity of the continuous fermentation leads to a smaller fermentation volume. And the continuous process needs less manpower. The ethanol yield is with 89–93% slightly lower than in batch fermentation. Further restrictions are the rather uniform raw material quality needs. Continuous sterilization of the medium is needed to avoid contamination. Nevertheless, the risk of contamination is higher than in batch fermentation due to long time performance.

In industry, both fermentation systems are in use for starch-based ethanol plants in Europe. For example, a continuous fermentation process is used in Zeitz in Germany and a batch fermentation process is implemented within a plant in Galicia in Spain. In Brazil, approximately 75% of all existing ethanol plants use the batch fermentation process. The main reasons for that are higher production stability and lower risk of contamination [9].

Distillation and Rectification The main target of the fermentation is to convert nearly all sugar into ethanol. The next step within the overall process is the recovery of ethanol from the fermentation mixture (beer). This is done by applying a combination of distillation and rectification columns. A simplified scheme with the two columns can be seen in Fig. 2.

To separate the ethanol from water the whole fermentation broth has to be heated up until the boiling point of this mixture is reached. The boiling point of pure water is 100°C compared to 78.33°C of pure

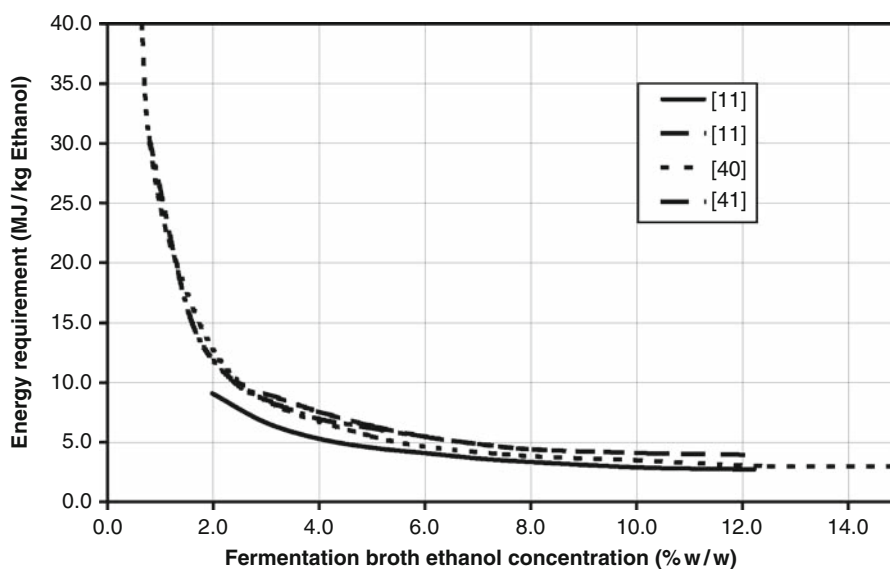
ethanol [10]. The actual boiling point of the mixture depends on ethanol concentration [7] and comes closer to the ethanol boiling point with increasing ethanol concentration.

The evaporation takes place according to their vapor liquid equilibrium which leads to a higher concentration of ethanol in the vapor. Unfortunately, the ethanol–water mixture is not an ideal system and shows a so-called azeotrope with a minimum boiling temperature of 78.15°C. The azeotrope is a point where the concentration of the liquid phase is the same as the vapor phase. The ethanol water azeotrope is at around 96.5% (v/v) according to 95.57% (w/w). This concentration is the limit for the rectification process. Therefore, an additional separation process for dehydration of ethanol is needed (see entry “Dehydration of Ethanol”).

Depending on the ethanol concentration in the fermentation mixture which is in the range of 12–20% (v/v) (corresponding to approximately 10–16.5% [w/w]) it can be seen in Fig. 3 that the energy needed to concentrate ethanol to 94% (w/w) is around 2–3 MJ/l. This energy demand is nearly constant for this concentration range. To reach these values, an optimization and energy integration of the whole downstream processes needs to be applied.

It is very important, especially in the stripping section of the first column where the whole fermentation broth is feed in, that precautions are made to avoid the blocking of the column internals with the solid matter of the mixture. Therefore, very open tray constructions are used which can cope with this kind of mixtures. Concentration of the derived vapor phase in the rectifying part of the following columns is like in any other ethanol processing plant and dominated by the vapor liquid behavior of the ethanol water mixture [7, 11].

Dehydration Around the globe, there is not a common standard for the fuel ethanol quality. The allowed maximum of the water content is 0.2–1.0% (v/v) and depends on the country in which the ethanol is sold [12]. For concentrating the ethanol from 94% (w/w) (nearly azeotropic mixture) to the required quality several options are possible. The first option is continuing with an azeotropic rectification process which needs two additional columns and a third component added to the mixture to change the vapor liquid behavior [13–15]. Alternatively, an adsorption process can be applied [16, 17]. Also a membrane processes called pervaporation or vapor permeation can be used [18–20].



Bioethanol from Starch. Figure 3

Energy requirement for concentrating ethanol from fermentation broth concentration to a rectification column top product with 94% (w/w)

In Brazil, still many plants use an azeotropic rectification process using monoethylene glycol for dehydration of ethanol. That technology has been developed more than 10 years ago especially for these plants in Brazil. Its advantages are lower investment costs and high robustness on the industrial scale [9]. In the USA and also in Europe, most of the ethanol plants apply the pressure swing adsorption process using molecular sieves for removing water from ethanol to reach the necessary fuel grade. The molecular sieve is a special designed hydrophilic zeolite with a pore diameter of about 0.3–0.4 nm. This allows only water with a molecular size of 0.28 nm to enter and ethanol with a molecular size of 0.44 nm is not able to enter the zeolite. For the technical process, at least two vessels filled with the zeolite are needed. One vessel is used for adsorbing the water from the ethanol vapor stream at around 1.7 bar [21]. The adsorption pressure applied depends on the design of the distillation and rectification system in which the column pressure is increased from the distillation to the rectification section due the energy optimization reasons. So that on the top of the rectifier column a vapor stream is received with respective pressure. In the second vessel at the same time the zeolite is regenerated applying vacuum and a small purge stream of already purified ethanol vapor. This purge stream removes the adsorbed water and after regeneration the cycle starts again. The purge stream with the increased water content from this desorption process is feed back to the rectification column (Fig. 2).

After the dehydration process, the ethanol stream is ready for use and stored in a tank. During the storage and handling one has to take care that due to the hygroscopic nature of the ethanol humidity is not allowed to come in contact with dehydrated ethanol.

Processing of Stillage The remaining liquid stream from the distillation column (beer column) after ethanol removal is called stillage. The maximum remaining ethanol concentration allowed is in the range of 0.02% (w/w). In some plants the untreated stillage is recycled up to around 25% to the liquefaction vessel.

The remaining stillage coming from the beer column contains solids like the yeast cells and also dissolved matter like salts and other nutrients. Usually a solid liquid separation is applied using a centrifuge or

a decanter. This treatment results in a thin stillage stream (with dissolved matter from the feedstock) and a wet cake (containing the solids with a dry matter of around 25–35%). Depending on the used feedstock, a high recycling rate of the thin stillage is possible. For example by using corn as feedstock, the possible recycling rate can be up to 75%. With wheat and triticale only 60% of recycling is possible [22].

The rest of the thin stillage is feed into a multistage evaporation system for further concentration. Using four or more integrated evaporation stages the steam requirement for evaporation can be reduced to 200 kg steam per ton of water evaporated. In the evaporation process a stream called syrup is produced. The evaporation condensate can be feed back to the mashing vessel to be used again and to reduce the fresh water consumption.

In the next step, the syrup is mixed with the wet cake and feed to the drying system. Here DDGS is produced. The drying procedure is, due to high heat of evaporation of water, very energy intensive. The mixture of syrup and wet cake is very viscous and very sticky. Therefore, it is rather difficult to treat. In addition, smell and dust emissions during processing have to be kept very low. As a drying technology, direct or indirect drying can be applied. The technical equipment is a rotary or drum dryer. For better handling the DDGS product is often pelletized (see [7, 23]).

The derived DDGS product is a protein-rich animal feed with a crude protein content of around 30% or more [24]. In Table 2, the estimated amount of DDGS produced for different feedstock can be found. Depending on the original used biomass some differences can be observed. In Table 3, an example is given for DDGS quality derived from ethanol fermentation with wheat and corn and a mixture of thereof as a feedstock [25].

DDGS as a product contributes to the economy of the process but also increases the energy needed for the ethanol and DDGS production approximately by a factor of 2. The results are higher energy costs needed for the process. This also has an effect on the environmental situation of the ethanol production itself.

Another possibility is to use DDGS as a source of energy within the ethanol plant. This could be of financial benefit if the costs for energy and the earning for DDGS do not match. Therefore, in many countries

Bioethanol from Starch. Table 3 Chemical characteristics of DDGS (% w/w DM) derived from corn, wheat/corn mixture, and wheat [25]

Value	Corn	Wheat/corn (4:1)	Wheat
Moisture	11.8	8.0	8.1
Crude protein	30.3	42.4	44.5
Nonprotein nitrogen	5.4	12.4	10.2
Crude fat	12.8	4.7	2.9
Ash	4.8	5.0	5.3
Acid detergent fiber	14.6	19.5	21.1
Neutral detergent fiber	31.2	30.6	30.3
Crude fiber	7.0	7.8	7.6

such projects are evaluated [26]. DDGS as a fuel could provide more energy than the ethanol plant itself needs since the energy content is rather high. This means that still some of the DDGS could be sold as animal food. The major drawback is that the very high nitrogen content leads to a very high NO_x concentration in the flue gas when the DDGS is used as a solid fuel. Additionally due to the high sodium and potassium concentration, the ash shows a rather low melting point. Therefore, the use of DDGS as a solid fuel is a less promising option.

Stillage can also be used as a feedstock for biogas plants [27]. The amount of stillage produced within an ethanol plant depends strongly on the size of the plant. Therefore, for large ethanol production facilities very huge biogas plants would be needed. Additionally, problems might occur concerning the direct usage of the digested residue in agriculture due to necessary transport or pumping cost. Further treatment using simple filtration or membrane filters would allow higher concentration and would lead to a reduced liquid volume for further handling.

The stillage contains different amount of organic dry matter depending on the feedstock used for ethanol production. Therefore, the possible biogas production might vary significantly. For example, it is possible to produce from corn stillage $0.347 \text{ m}_N^3/\text{kg oDM}$ and $0.380 \text{ m}_N^3/\text{kg oDM}$ from the wheat stillage [28]. A general layout of an ethanol biogas concept can be seen in Fig. 4.

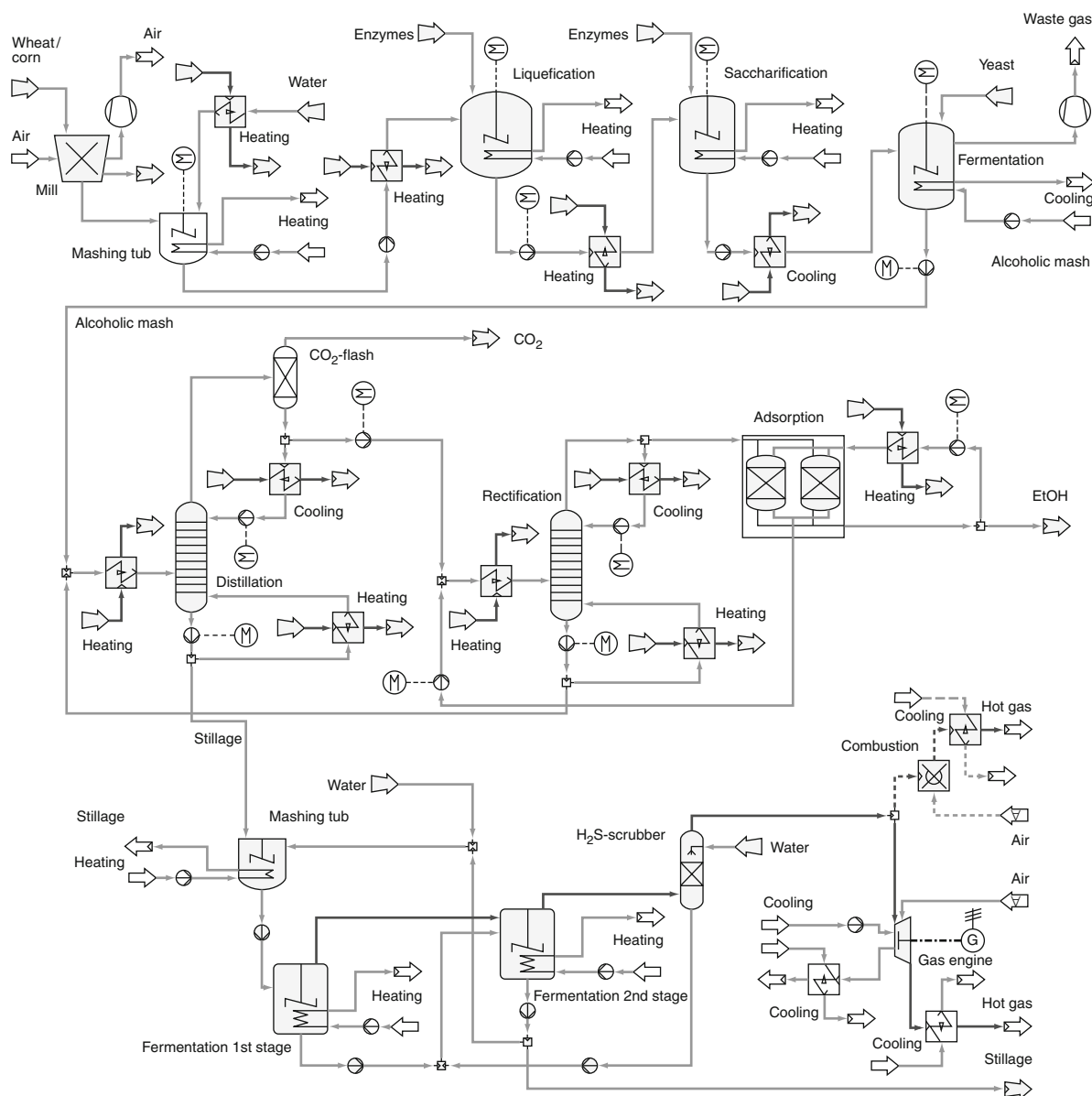
The biogas produced can be used in many different ways. It is possible to use it directly in a gas-fired boiler for steam production to cover the energy requirement of the ethanol plant as well as for electricity production (if the biogas production facility is big enough). Or it can be used for electricity production in a biogas-fired engine within a CHP process. Such process combinations together with optimized process integration can lead to a significant decrease of the energy demand of ethanol production [29].

Actual Status

A large-scale ethanol production has been realized within the USA for more than 30 years. The main source of feedstock used is grain. In Europe, the large-scale ethanol production as a fuel started in 2003, initiated by the European Parliament and the Council with posting the directive 2003/30/EC on the promotion of the use of biofuels or other renewable fuels for transport [30]. Since then many new ethanol plants have been built within EC-Countries to meet the requirements of replacing at least 5.75% of fossil fuel by biofuels based on the energy content by 2010. Single European countries enacted individual laws to follow the EC directive and in several countries even a tighter time schedule has been applied. For example, in Austria in 2004 a change in the existing fuel legislation [31] posted for October 1, 2005, a value of 2.5%, October 1, 2007, a value of 4.3%, and already on October 1, 2008, a fulfillment of the EC legislation of 5.75% based on the energy content.

The strong efforts of the USA and the EU in contributing significantly with biofuel to cover the energy demand within the transportation sector led to the situation that the USA passed Brazil as the world's largest annual ethanol producer in the year 2005 where both countries produced around 16 million cubic meters of ethanol. The world production in this year was 46 million cubic meters of ethanol. Since then the annual production capacities increased steadily worldwide to 74 million cubic meters ethanol in 2009 with 41 and 25 million cubic meters ethanol in the USA and Brazil respectively [32].

Analyzing these figures it can be estimated that around the year 2000 the ethanol production was 60% from biomass containing sugar and 40% from



Bioethanol from Starch. Figure 4

Schematic layout of a dry-mill ethanol process including Biogas production

grain crops (i.e., starch). Between 2000 and 2009 the situation changed to a ratio of approximately 40% from sugar crops and 60% from grain crops.

Following the trend of increasing production figures of ethanol, increasing amounts of starch crops are needed as a feedstock. The world production of grain crops in the period 2008/2009 was 2,231 million tons (without rice). This was around 5.2% above

the production of the year before 2007/2008 and has been the world's best production year ever. The prognoses for the year 2009/2010 are 2,196 million tons (without rice) which should be the second best production year ever. These record years in harvest are following after a deficit production in the year 2006/2007 which was followed by a very steep increase of price for the grain crops. A worldwide reaction was to

increase the land for grain crop production by 16 million hectares [33].

In the year 2008/2009, the worldwide harvest of corn was 791.9 million tons and that of wheat 682.8 million tons. In the European Community of 27 states (EC-27) the harvest of wheat was in the same year 315.2 million tons. For ethanol production, 5.0% of the wheat was used in the EC-27 in this period. Within the USA at the same period approximately 12% of the world corn production has been converted into ethanol [33].

Future Directions

After the rapid increase of large-quantity production of ethanol in a rather short time, it is important to continue on a settled basis to implement all experiences learned. This includes politics, environment, agriculture, and the ethanol process itself. The learning curve of the Brazilian and US ethanol industry over the last 30 years made it possible to reduce the production costs by more than 60% [34, 35]. This fact shows how important continuous process improvement is. For example, in the Brazilian ethanol industry it was possible to increase the fermentation yield from 75% to 92% based on the theoretical maximum during this time [9] which of course contributes significantly to the economics of the overall process. Actual production costs are estimated approximately with \$188/m³ in Brazil and \$310/m³ in the USA [35]. In Europe the estimated productions costs are around \$500/m³. Due the fact that Europe started large-scale ethanol production for the use as a fuel in 2003 [30] it can be expected that due to significant improvements the production costs of ethanol in Europe can be reduced in the future.

Further developments are already initiated from the European directive 2009 [36]. This regulation demands that on January 1, 2017, a 50% GHG saving target and on January 1, 2018, a 60% GHG reduction target have to be met. To reach these goals, the ethanol-producing industry is forced to improve the efficiency not only in the ethanol production process itself but also in the whole production chain to receive a better environmental performance.

This will influence the developments in all areas linked to the bioethanol production in industry and

research. The latter is urgently needed along the overall process chain to identify and exploit the given GHG reduction possibilities. On the agricultural side, crop developments are necessary to maximize starch production and lower pentosan and glucan concentration (responsible for high viscosity in the broth) with lowest environmental impact. Additionally, the existing substrate basis has to be extended. The use of various sugar, starch, and lignocellulosic material streams, or even mixtures will be needed to accomplish the given demands.

For the ethanol process itself, the optimization of the enzymatic steps and the fermentation process with high solid content is needed to provide together with optimized ethanol-producing microorganism high ethanol concentration at the end [37]. One route for optimization of the fermentation could be the removal of the remaining rough grain after dextrinization during the dry corn milling process. This would lead to an approximate 11% volume reduction of the fermentation vessels. Energy savings along the fermentation and distillation processes are the result since energy for cooling of the insoluble particles and heating in the distillation column is avoided.

At the moment, most of the dry grind fuel ethanol plants using the SSF process. Wet milling technology leads to solid-free mashes, which makes the yeast separation possible and water as well as yeast recycling can be done to a higher extent. The distillation will receive a solid-free stream which makes this step easier. The question is how the fermentation conditions (e.g., temperature, feeding of the carbon source) need to be set? This should be a mid-term program of further research activities because the question of the optimal balance between the fermentation time, the final alcohol concentration and yeast cell viability will strongly influence the economic situation of ethanol plants in the future [9].

In the downstream part, the process intensification with the help of membrane processes needs to be investigated. A first step in this direction is a large-scale pervaporation plant for ethanol dehydration from about 93% (w/w) to a quality of 99.5% (w/w) [20]. Further optimization would be possible if the inlet concentration of the energy-effective pervaporation plant could be reduced to 70% (w/w). This would result to a significant energy saving in the rectification

column. An energy-saving potential of 30–50% could be achieved [38]. The next step of optimization would be the application of an alternative process combination like stripping and membranes to perform ethanol separation from the fermentation broth itself. If a concentration of 70% (w/w) can be reached in the first process step this would close the gap between the second membrane separation steps for dehydration. This would avoid the energy-intensive distillation and rectification totally [39].

Furthermore, alternative usages for the stillage will be needed due to the large increase of worldwide DDGS production. This increase already significantly influences the whole fodder market. Expected limits of DDGS demands would result in falling prices. Since the stillage contains proteins, betaine, lipids, and organic acids and within the yeast cell most nitrogen is fixed in vitamins it might be possible to recover products with high selective and cost-efficient separation processes. The use of the stillage itself for the biogas production is from the environmental point of view a very interesting option. But it might be restricted to small- or middle-scale ethanol plants without effective separation process to increase the solid load of the biogas fermenter and to reduce the water demand significantly. This is also an important task for research. The suspected high nitrogen content in the liquid has to be taken into account. A main advantage of the biogas option is that the nitrogen is kept in the liquid phase, and is not lost as it is in DDGS incineration. This nitrogen can be used as a fertilizer in the agriculture which again improves the environmental performance due to reduced need of mineral fertilizer.

After all optimizations, a remaining demand of energy will be needed to drive all the processes along the ethanol production chain. For this energy needed, the optimal application of renewable energy will be important.

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Bioethanol from Sugar: The Brazilian Experience

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Article Outline

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The State of the Art on Sugarcane Ethanol
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Glossary

Biofuel Biofuel is one type of bioenergy. In general, this term is used for liquid biofuels. The most known liquid biofuels are biodiesel and bioethanol.

Biofuel program In general, encompasses incentives to biofuels production and/or consumption through policies and regulatory frameworks.

Biomass Biomass is anything that has lived from vegetal or animal origin. The energy obtained from biomass (such as wood, straw, crops, etc.) to produce a fuel is known as bioenergy.

Energy balance Energy balance is the assessment of the energy content in a certain biofuel compared with the fossil fuel energy used to convert it.

Replication Repetition of an experiment utilizing key features. Following the Brazilian experience with ethanol, other countries have possibility to convert sugar plants into ethanol distilleries.

Sustainability Sustainability of biofuels production is related to environment protection, social welfare, and economic development.

Sustainable development Sustainable development is the utilization of the resources aiming to achieve better living conditions without disturbing the future generations' needs [1].

Tariff and non-tariff barriers Tariff barriers are duties imposed on tradable goods and services to be imported. Non-tariff barriers are a way to delimitate the trade by imposing conditions, quotas, and restrictions. Tariff and non-tariff barriers are barriers imposed mainly by developed countries against the import of products which may jeopardize local economy (or local farmers); they also occur in biofuels trade [2].

Definition and Importance of the Subject

The Brazilian ethanol program (Proalcool) is the oldest of such programs and started in 1975, producing ethanol from sugarcane. A similar program using corn was initiated around the year 2000.

The 2009 world's ethanol production was 76 billion liters – of which 41 billion is in the United States (USA) and 26 billion comes from Brazil – equivalent to 34.8 million tons of oil equivalent or 1.5% of total world oil consumption. The rest of it comes from different countries, mainly Europe and China. Ethanol production is increasing in several regions of the world: Of the 24 producing countries, there are 14 countries in Europe and 5 countries in Asia and Pacific area.

Since transportation is almost entirely dependent on petroleum products, liquid biofuels represent an option to address this challenge in the transportation sector, where there is no other renewable energy commercially available. It should be emphasized that 14% of the world greenhouse gases emissions come from transportation sector.

The main increased importance of biofuels is closely related to the current energy challenges, which are energy security, global warming, and the increasing energy needs of developing countries. This entry presents an overview of the Brazilian experience, lessons learned, and current policies to guarantee the production of biofuels in a sustainable way, as well as, perspectives for replicating it in other developing countries.

Introduction

From a technical perspective, there is nothing new in the renewed interest in using biofuels in internal combustion engines. Late in the nineteenth century, Henry Ford already used ethanol to drive automobiles and Rudolf Diesel used biodiesel from peanuts to drive trucks.

In the beginning of the twentieth century, these fuels were replaced by gasoline and diesel oil distilled from petroleum due to their higher affordability and availability in the USA and a few other countries with easy access to oil, while biofuels, particularly ethanol (an alcoholic beverage), were expensive and produced in minor quantities when compared to the huge quantities needed for large vehicle fleets.

In case of Brazil, since 1920, technical studies have been conducted in Brazil on ethanol-run vehicles, including racing cars. The reason for that was the good performance of ethanol used for fuel purposes, which made it a good alternative to imported gasoline. The first Brazilian policy supporting bioenergy was launched in 1931. The Brazilian Decree No. 19,717

required that all imported gasoline had to be blended with 5% of bioethanol from sugarcane. Later on, in 1938, this blend was extended to the gasoline produced in the country through the Law No. 737. The blend remained around 5.5% from 1935 to 1945 [3]. Over the years, the blend remained almost constant and slowly reached 7.5%. Such blend did not require any changes in the engines.

By the early 1970s, Brazil imported most of gasoline and petroleum consumed in the country, at an annual cost of US\$600 million. In 1973, with the first oil price shock, imports rose to more than US\$4 billion annually, contributing greatly to the deficit in hard currency and badly damaging the economy.

This was indeed a turning point, where the ethanol was no longer deemed as a by-product of sugar. In November of 1975, The National Ethanol Program, which is known as Proalcohol, was established. This program was the Federal government reaction to the “oil shock” and was created by the Decree No. 76,593. The program also served to assist sugar sector that was facing problems due to the low sugar price in the international market [4]. The production targets were set for 3 billion liters of ethanol by 1980 and 10.7 billion liters in 1985.

There were two distinct phases in the program. The first phase occurred from 1975 to 1979, emphasizing the production of anhydrous ethanol for gasoline blending as an additive to substitute MTBE (methyl tertiary-butyl ether), which is an ether added to gasoline to increase the octane by given oxygen to the combustion reaction. Once ethanol was added to gasoline, MTBE was eliminated as an additive. Ethanol has higher octane number than gasoline and performs the same role as MTBE without the presence of the toxic lead.

Other support actions to increase the competitiveness of ethanol were low interest loans for the construction of distilleries, guaranteed purchase of ethanol by the state-owned petroleum company (Petrobras), and subsidies. In this phase, gasoline was blended with 20% of ethanol and it was adopted a fixed price system, where 44 l of ethanol corresponded to 60 kg of sugar.

The time frame of the second phase spanned from 1980 to 1985, when the focus was on the production of hydrous ethanol for engines designed to run this fuel. The supply side was stimulated by diminishing the

parity of 60 kg of sugar to 38 l, and for the demand side, there were incentives among others over the fuel price and taxes reduction [5].

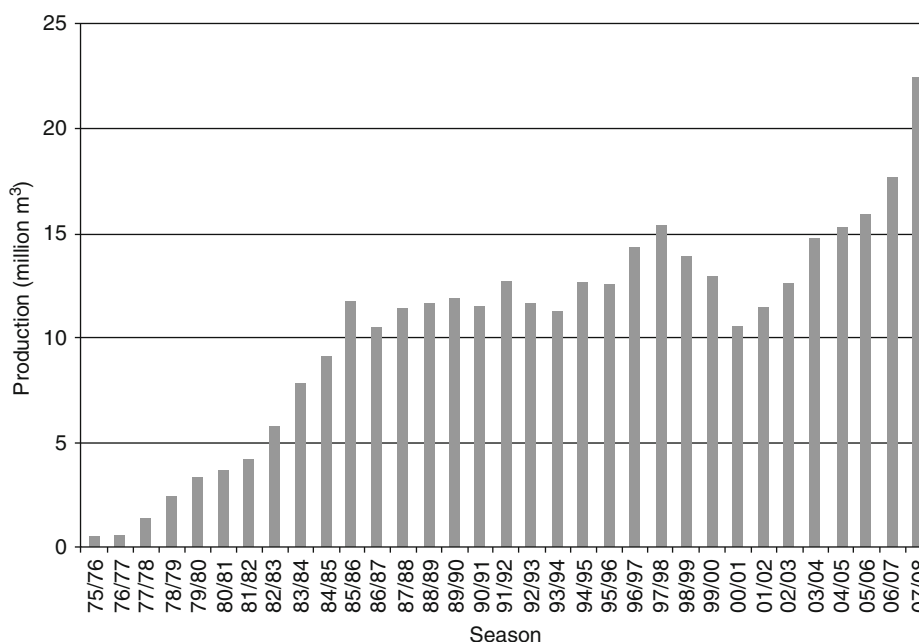
The background of the technological development of engines to run pure ethanol started in 1975 when the Federal Government learned about the research done by the Air Force Technological Center in São José dos Campos, São Paulo to develop ethanol-fueled cars using hydrated ethanol in a proportion of 95.5% pure ethanol to 4.5% water. Important changes in the engine were necessary in order to use that fuel.

One of those changes was the compression ratio that is 12:1 for ethanol fuel from sugarcane, while regular gasoline requires compression ratio of 8:1. Higher compression ratio signifies higher efficiency, which is partly compensated by the lower energy content in the ethanol. For the sake of the clarity, energy equivalence between the two fuels takes into account the final energy service provided. In this way, 199 l of pure (anhydrous) ethanol can replace one barrel of gasoline (159 l). The necessary changes in the engines to run ethanol meant a drastic change in automobile manufacturing, but under governmental pressure, local automobile manufacturers adjusted to that.

Sugar producers welcomed these changes that let them divert more sugarcane to ethanol production, and faced better oscillations in sugar prices in the international market. Another enthusiastic support came from nationalistic elements in the government, who saw ethanol as an instrument of national independence. One of the consequences was that driving Brazilian car with engine designed to run ethanol in neighboring countries (even some States of Brazil) was a problem because they did not have filling stations selling hydrated ethanol. The production of cars with pure ethanol engines began in 1978 with the participation of manufactures such as General Motors (Opel), Ford, Volkswagen and Fiat. Between 1979 and 1985, they accounted for 85% of all new car sales [6].

Over the same period, the percentage of ethanol in gasoline reached approximately 20%. The evolution of Brazilian ethanol production since beginning of the Proalcohol is illustrated in the Fig. 1.

Therefore, two types of automotive vehicles were present in the country: some running on gasoline, using a blend of up to 20% anhydrous ethanol and 80% gasoline, and others running entirely on hydrated



Bioethanol from Sugar: The Brazilian Experience. Figure 1
Evolution of ethanol production in Brazil [7]

ethanol. Nevertheless, it is important to mention that the targets were achieved through mandatory regulations, subsidies, and due to the unique characteristics of the country at that time, since Brazil was under an authoritarian government from 1964 to 1985.

In 1985, the scenario changed dramatically, as petroleum prices fell and sugar prices recovered on the international market. Subsidies were reduced and ethanol production could not keep up with demand. Therefore, by 1990, sales of cars running on pure ethanol dropped to 11.4% of the total [8].

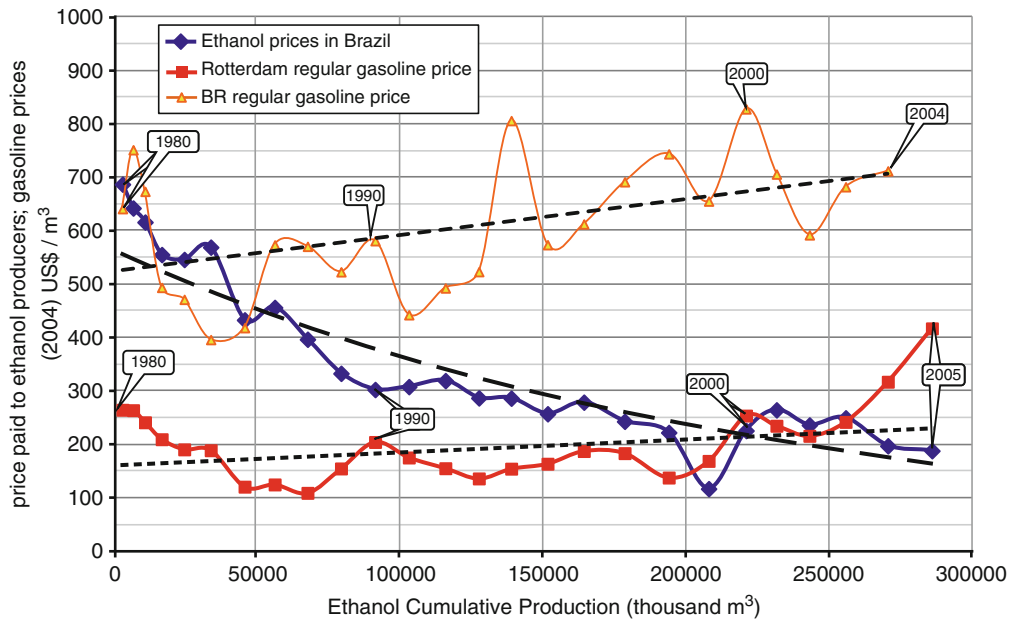
The production of ethanol leveled off, but the total amount being used remained more or less the same because the decrease of hydrous ethanol cars was compensated by the increase on gasoline blending to 25% (Fig. 1). From 2003 onward, with the advent of flex fuel engines, ethanol consumption started to rise again. Since 2003, Brazilian automotive industry has introduced the so-called flex fuel vehicle, which means a vehicle running with any ethanol gasoline blend, from E-0 up to E-100. It must be noted that the Brazilian flex fuel vehicles are different from those produced in other countries (like USA), which can run with a maximum of 85% ethanol (E-85) only.

These cars are built to use pure ethanol with a high compression ratio (approximately 12:1); however, they can also run with any proportion of ethanol and gasoline, from zero to 100%. The increasing in the productivity of ethanol was reflected in costs (Fig. 2).

In 1980, ethanol cost roughly three times as much as gasoline in the international market (Fig. 2). And, since 2003, ethanol became fully competitive with gasoline without any subsidies. It is important to emphasize that this achievement is result of over 30 years of experience with technological gains, economies of scale, and political effort from policy makers and other stakeholders.

The expansion of ethanol production had important repercussions in the ownership and management of the sector, which in Brazil is entirely in the hands of private groups. Although Petrobras, the state-owned Brazilian oil company, is beginning to invest in this area, it is still a very small player [10].

Traditionally, sugar-producing units were family-owned enterprises such as Costa Pinho, São Martinho, and Santa Elisa, but new ones are owned by Brazilian companies including Votorantim, Vale, and Odebrecht. Also there are foreign companies entering the



Bioethanol from Sugar: The Brazilian Experience. Figure 2
Brazilian ethanol learning curve [9]

sugarcane business, including French (Tereos, Louis Dreyfus), Spanish (Abengoa), British (BP) and Japanese (Mitsui, Marubeni) groups, among others.

The financial sector is also quite active in this area, including Merrill Lynch, Soros, and Goldman Sachs. The presence of foreign investors has given the sector a new dynamism and new concepts of management.

Ethanol from Sugarcane

Sugarcane

Brazilian ethanol is produced from sugarcane (*Saccharum officinarum*), which is not an indigenous plant from Brazil.

In 1532, sugarcane was brought to Brazil by the Portuguese during the colonization period. This plant is a type of grass that has fibrous stalks containing high concentration of sugar. In order to achieve a good development, sugarcane needs distinct climate seasons. One phase is dedicated to germination, in which adequate rainfall and higher temperatures are necessary. During the phase for sucrose accumulation, it can be colder and dryer. The cultivation requires a minimum rainfall of 1,200–1,300 mm a year, in order to avoid

irrigation, and the ideal temperature ranges from 20°C to 24°C because this plant is not resistant to cold weather [10].

Brazil is a tropical country, and many of its regions have favorable climate characteristics for sugarcane cultivation without irrigation. Sugarcane is a semi-perennial crop, that is, after the planting phase, sugarcane can be harvested six to seven times without replanting; however, it is recommended one season of rotation with a different crop to rest the soil. This practice is common throughout the country.

Thus, in each harvesting season, 20% of the crop is replaced with crops that help to recover the soil such as beans, corn, or peanuts. The harvesting season follows the rainfall pattern of every region. As such, in the Center-South production region, it starts in April and finishes in December and in the North-East region, it spans from August to April. Depending on industrial process, sugarcane is transformed either in sugar or ethanol.

Sugarcane is the feedstock for alcohol (ethanol fuel, pharmacy or beverage), sugar, and electricity from bagasse as well. Vinasse (stillage), bagasse, filter cake, tops, and leaves (trash) are by-products from sugarcane that are also utilized in modern practices.

Bagasse (30% of the cane, 50% wet) is the remaining fibrous part of sugarcane after the crushing. It is rich in cellulose and contains more energy (560 Mcal/t of sugarcane) than ethanol itself (392 Mcal/t of sugarcane) [11]. This by-product is burned in boilers, providing heat and electricity.

Vinasse is generated from distillation. It consists of a liquid rich in organic matter and nutrients, such as potassium and calcium, but it is also a pollutant if not well managed. Vinasse production is around 10 l per liter of ethanol, but new technologies like vinasse concentration allows the reduction on the production of vinasse until 5 l for 1 l of ethanol (Magazoni LA, personal communication, magazoni@cerradinho.com.br). The use of vinasse in fertirrigation practice reduces the need for fertilizers and gives a no pollutant destination to this by-product. It must be noted that in the State of São Paulo, the use of vinasse for fertirrigation is controlled by the Environment Agency (CETESB) aiming to avoid contamination of underground water. This requirement will be probably followed by other States in Brazil.

Filter cake is also a by-product from juice filtration. It consists of rests of bagasse and sugar clarifier sludge, eliminating by 50% the need for phosphorus mineral fertilization. The production proportion for each ton of sugarcane milled varies from 30 to 40 kg of filter cake [11]. Tops and leaves (trash) represent 30% of the sugarcane. In many cases, they are the leftover of the harvesting and also left on the soil as preventive method avoiding erosion and nutrient depletion or utilized as cogeneration fuel.

From Field to Motor

Ethanol or ethyl alcohol is an organic compound that belongs to the first generation of biofuels (Box 1). Typically, ethanol is obtained through biological conversion involving fermentation process, which converts sugar into alcohol.

After the harvesting, sugarcane must be transported and processed in maximum of 72 h in order to avoid quality losses due to bacterial activity [12].

In the distillery, the grinding breaks the sugarcane fibers. Subsequently, acids or enzymes are added in

Box 1: Definitions of First- and Second-Generation Biofuels

First-Generation Biofuels The common forms of first-generation biofuels are those on the market in considerable quantities today. Typical first-generation biofuel is sugarcane ethanol, starch- or corn-based ethanol, biodiesel, biogas, and pure straight vegetable oil. The feedstock for producing first-generation biofuels are crops that produce sugars, starches, oils, or animal fats, most of them being food and feed, as well. It also can be obtained from residues. Other niche of biofuel is biogas, which results from an anaerobic treatment of manure, urban residues, and other biomass materials. Relatively small volumes of biogas are currently used for transportation. Today, the first-generation biofuels commercially produced is about 76 billion liters annually.

Second-Generation Biofuels Second-generation biofuels are those biofuels produced from cellulose, hemicellulose, or lignin. Examples of second-generation biofuels are cellulosic ethanol, Bio-SNG, and Fischer–Tropsch fuels. The latest technology synthesizes fuel from gases produced from the gasification of biomass. Both, first and second generation of biofuels can be blended with petroleum-based fuels, combusted in regular internal combustion engines, distributed through existing infrastructure. In addition, second generation may also be utilized in slightly adapted vehicles with internal combustion engines like vehicles designed to run Di-Methyl Ether (DME). According to Petrobras [17], the first bioethanol pilot plant has started activities utilizing enzymatic technology to convert waste into biofuels. Even though the second-generation biofuels are meant to be more sustainable, this technology needs technological breakthrough to reduce the production costs. Besides, second-generation biofuels are still in the development stage and production cost seems to be higher compared to first-generation ones.

Source: Reference [18].

order to precede the hydrolysis and obtain glucose. The glucose is then fermented to produce ethanol by the action of adequate yeasts.

Two important chemical characteristics of ethanol that should be emphasized are the boiling point (78.5°C) and the miscibility with water and organic components. There are two types of ethanol: The anhydrous form is used to blend gasoline and the hydrated one is used as fuel in engines specially designed for this type of fuel or flex fuel motor. The difference between the two types is the water content in the anhydrous and hydrated, which is 0.5% and 5%, respectively. Pure gasoline is called “gasoline A” and the gasoline blended with ethanol is “gasoline C” (gasohol). The percentage of ethanol blend in the “gasoline C” might range from 20% to 25%, according to the current legislation being regulated by The National Petroleum Agency (ANP). Among the ANP functions, supervision and control of the biofuel market is included.

Energy balance can be defined as the ratio of total fossil fuel energy required for the biofuel production process to the energy contained in the biofuel produced [13]. Energy balance of biofuel produced from a feedstock might be an indicator of the sustainability when taking into account greenhouse gas emissions avoided in a life cycle basis. A study on sugarcane ethanol energy balance shows significant differences between feedstock, where the energy balance of the

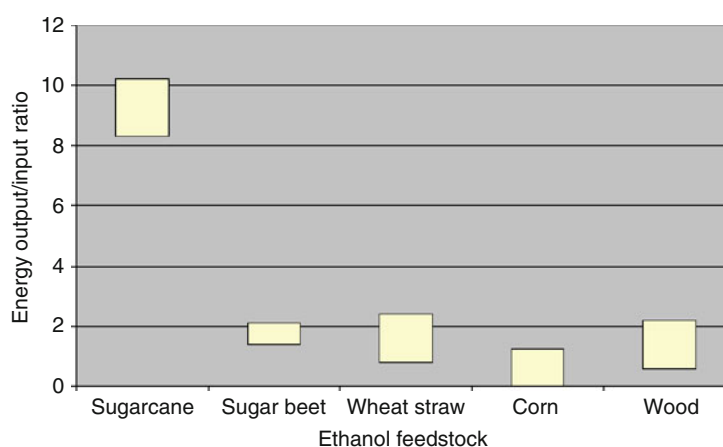
ethanol produced from sugarcane is 8.9, from sugar beet 2, and from corn 1.3 (Fig. 3) [14]. The sugarcane ethanol presents less GHG emission compared to fossil fuels due to the nearly closed carbon cycle. In respect of land use, feedstocks with higher yields per hectare require less quantity of land.

The good performance of the ethanol produced from sugarcane is due to the use of sugarcane bagasse that provides the energy needs for the process, eliminating external sources of energy. Bagasse is the most important by-product from sugarcane, and it is burned in the boiler producing both mechanical and electrical energy (i.e., cogeneration, see Sect. “Cogeneration in Sugarcane Mills”).

Another by-product that is increasingly growing in importance for energy generation to the process is the sugarcane leaves. This is happening due to the progressive decrease of the burning practice of sugarcane before harvesting and the progressive introduction of green cane harvesting.

Country Profile

Brazil is a large country and since the Proalcool program, it has always been an important player for ethanol production in the world. In order to give an idea of this country profile, the main social,



Bioethanol from Sugar: The Brazilian Experience. Figure 3
Energy balance from ethanol production from different feedstocks [14–16]

demographic, and economic indicators are summarized in the [Box 2](#), as well as, relevant information regarding production and use of ethanol.

Box 2: Brazil in Figures

The Federal Republic of Brazil has a continental size, 8,514,876 km². In 2008, the total population was 194,228 million inhabitants [19], and in 2007, the population growth was 1.2% [20]. Regarding economy, the Gross Domestic Product (GDP) corresponded to 2.4% of the world's GDP [20]; with 10% participation of agricultural sector [21]. Regarding the wealth distribution, in 2008, the Gini index was 57 [22]. The Human Development Index (HDI), which is a more complete index encompassing educational level, longevity, and income dimension, was 0.807. Yet, concerning HDI, in 2008, the country was positioned at the 70th place [23] in the world. Brazil is the second largest producer of ethanol in the world with 26 billion liters in 2009 [24]. This amount accounted for 37% of the world's production. This country is the world's largest sugar producer, with 622 million tons (metric tons) in the 2008/09 harvesting season [25]. In Brazil, the mills can be either a sugar plant or alcohol distillery or sugar mill and alcohol distillery. Most of the 414 existing Brazilian mills (60%) are alcohol distilleries attached to a sugar plant. In the period of 2008/2009, 35 new distilleries were to start production and another 43 were in different stages of development. In order to process quickly the feedstock, the sugarcane distilleries need to be close to the sugarcane plantation. The Center-South region responds for nearly 80% of ethanol production in the country. There is a high concentration of distilleries in the Center-South production region, but with no pressure against the Amazon or other important biomes in the country. Today Brazilians are driving about 24 million automobiles. In 2000, there were 2.8 million pure ethanol engine cars. Most of the pure ethanol cars have been retired while seven million of flex fuel cars are on the road and their numbers are increasing rapidly [26]. The huge success of these flex fuel vehicles is due to the freedom of choice for the consumers, depending on the price of each fuel at the gas station.

Sustainability Aspects of Sugarcane Ethanol

What are the issues regarding environmental, economic, and social aspects of the sustainability? Several studies [36, 65, 79] explored these issues deeply in recent papers summarized in this section.

Environmental zoning is a crucial tool to guarantee the sustainable production of sugarcane ethanol. There are such zonings in São Paulo State [27], in Minas Gerais State, and from the Federal Government. A recent environmental zoning for sugarcane (2009) from the Federal Government defined areas available for the crops and protecting biodiversity of important biomes named “Sugarcane agroecological zoning” a jointly effort from the Ministry of Agriculture and the Ministry of Environment. Besides that, there are studies [28] indicating that there is no scientific evidence that sugarcane crops present pressure on Amazon (Indirect Land Use Change – ILUC).

Environmental Aspects

In the beginning of the program, economic and strategic factors were crucial in reducing Brazil's dependence on oil, but later on, environmental preservation became also a key issue.

Ethanol engines present lower emissions than gasoline ones, such as no sulfur oxides or particulates, which are the primary cause of poor air quality in large cities like Beijing, Mexico City, São Paulo, and Los Angeles. In São Paulo, the air quality has improved remarkably since gasoline was partially replaced by ethanol. Nowadays, it represents more than 50% of the fuel powering vehicles.

Acknowledging that the main contributor to global climate changing is CO₂ from fossil fuel energy, ethanol has lower CO₂ emissions than gasoline because of the lower amount of CO₂ from fossil fuel energy produced over the ethanol life cycle. An important result was the approval from United States Environmental Protection Agency (EPA) [29] of the use of sugarcane ethanol, accepting that overall carbon balance is highly positive [28].

Besides, many environmental problems associated with oil production (spills), transportation (leakages), and consumption (emission of greenhouse gases (CO₂,

CH₄, N₂O), SO_x, NO_x, H₂O vapor and acid gases like HCl) are not present when using ethanol.

Therefore, below a brief overview of environmental impacts is presented, together with existing legislation to control them.

Water in Sugarcane Ethanol Production One of the most important issues related to water pollution in sugarcane industry was the adequate disposal of vinasse. Vinasse is a black liquid derived from distillation and fermentation, as already mentioned; this by-product is rich in organic matter with an acidic pH [4, 5]. It is a potential pollutant to water and can therefore not be discharged directly on rivers.

In the beginning of the program, there was no control on vinasse disposal from the mills and, in most cases, it was disposed in rivers, being responsible for high pollutant impacts. The solution to dispose this by-product was found, and it started to be recycled and used for fertirrigation. For some time, it was used for fertirrigation without any control. Therefore, the impacts related to the contamination of underground waters became important.

In 2006, in São Paulo State, the Environmental Agency (CETESB) started to control the amount of vinasse disposed on soils, aiming to avoid the contamination of underground water [30]. Nowadays, other states are also introducing the same control for the licensing of the mills.

Also there are now some initiatives aiming to reduce the amount of vinasse produced using systems for concentrating it (Magazoni LA, personal communication). By introducing such systems, the amount of vinasse produced decreased to 5 l per liter of ethanol produced.

Additionally, local environmental agencies all over the country are controlling the maintenance of riparian forests nearby sugarcane crops and requiring the reforestation of such areas with native forests, according the Federal Forest Code. In fact, it must be noted that this Code only states that it is forbidden to jeopardize the growing (or re-growing) of riparian forests. However, environmental agencies are requiring more than that: They consider mandatory the conservation (and/or reforestation) of these riparian forest of the plantations. This is an important issue, since it protects the quality of water in rivers.

Water is used in two ways in producing sugarcane and ethanol. Firstly, large quantities of water are needed to grow the cane. The cane requires significant rainfall, in the range of 1,500–2,500 mm a year, ideally spread uniformly across the growing cycle. Most of the sugarcane production in Brazil relies on rainfall, rather than irrigation, including nearly the entire São Paulo State sugarcane-producing region. Secondly, also large amounts of water are also used to convert sugarcane into ethanol. In 1997, this amount was calculated as cubic meters per ton of cane, from which 87% was used in four processes inside the plant.

In general lines, there is one process for sugarcane washing and three other industrial processes for ethanol production. Water consumption has substantially decreased in recent years. Furthermore, sugarcane is 70% water, which should provide enough for all the steps needed in ethanol production. There are distilleries being developed to be self-sufficient regarding water consumption. Also, nowadays the dry cleaning of sugarcane is being introduced in several mills, reducing the water consumption in the process (Magazoni LA, personal communication).

Land Availability Concerns related to the conservation of native forests and other important biomes are always presented and some studies even consider that any bioenergy crop comes from deforestation [31–33]. Notwithstanding, these studies only consider the worst case, which is not currently occurring, since biofuel production is not expanding into pristine tropical forests. If that did happen, of course, it would release a large amount of CO₂, but extensive studies have been conducted on the CO₂ releases resulting from other agricultural practices that do not involve deforestation, and the results are much less alarming [34]. Nevertheless, other studies [35] show that this is not adequate and bioenergy crops are being expanded in pasturelands without any deforestation.

In 2007, the land availability for agriculture in Brazil was 355 million hectares, from which 21% had already been used for agricultural purposes and the area occupied by sugarcane ethanol accounted only for 1.5% [7].

Moreover, there were 30% available land and 49% was occupied by pastureland. In this land, there is the possibility of expansion of agricultural crops, like has already occurred in the state of São Paulo through the

replacement of pastures, which have become more intensive [36].

In 2001, in the State of São Paulo, the average number of heads of cattle per hectare was 1.28. As of 2008, it has been increased to 1.56 because of the expanding sugarcane plantations pressuring cattle grazing. In the country as a whole, the density is even lower, at closer to one head per hectare [37].

The Brazilian sugarcane crops expansion is concentrated in the Center-South production region that does not encompass important biomes like Amazon Rain Forest, the Atlantic Forest, and the Pantanal [38]. The deforestation in the Amazon basin is linked closely with the raising of cattle for meat, for both domestic consumption and export; it is not linked with ethanol production. Today, Brazil has approximately 200 million heads of cattle on 237 million hectares [39]. In fact, if this cattle could grow in a more intensive way, reaching 1.5 heads for hectare (which is not yet an intensive growth), the country could have around 60 million hectares available.

In addition, recent studies [28] have analyzed Indirect Land Use Changes (ILUC), showing that there is no concrete evidence that sugarcane expansion is producing deforestation.

Soil Quality Sugarcane culture has become more sustainable over the years as some practices have been introduced insuring the appropriate use of fertilizers and soil protection against erosion, soil compaction, and moisture loss. In Brazil, some soils have been producing sugarcane for more than 200 years, with no yield reduction. In fact, agricultural production has increased significantly. Sugarcane culture in Brazil is well known for its relatively small loss of soil to erosion, especially when compared to soybeans and corn.

Nowadays, with the introduction of the green harvesting of sugarcane, a significant discussion is on the way, related to the amount of residues that should be left in the field to protect the soil. Studies show the importance of the sugarcane residues left in the soil, since they protect the soil and allow the infiltration of water in the soil and reduce erosion, among other benefits.

Agrochemicals Many inorganic compounds are introduced during the production of ethanol,

including chemicals that kill weeds, insects, mites, and fungi, along with defoliants and other chemicals that help the cane to mature more quickly. Concerning agrochemicals, fewer agrochemicals are used in sugarcane production than for some other crops. The pesticide consumption per hectare for sugarcane is lower than for citrus, corn, coffee, and soybeans. Nevertheless, sugarcane requires more herbicides per hectare than coffee.

Furthermore, comparing Brazil's major crops (those grown on areas larger than one million hectares), sugarcane uses smaller amounts of fertilizer than cotton, coffee, and oranges, and about the same amount as soybeans. Sugarcane also uses less fertilizer than sugarcane crops in other countries, for instance, compared to Australian sugarcane growers that use 48% more fertilizer than Brazilian ones [14].

One practice that helps here is using the vinasse as a fertilizer. This has led to a significant increase in productivity and in the potassium content of the soil [40]. Genetic research, especially the selection of resistant varieties, has made it possible to reduce the diseases affecting sugarcane, such as the mosaic virus, sugarcane smut and rust, and the sugarcane yellow leaf virus. With genetic modifications, plants are more resistant to herbicides, fungus, and the sugarcane beetle; some of these modifications are now being field tested.

Air Pollution Besides the advantages of sugarcane ethanol replacing gasoline in engines, with most of pollutant emissions being reduced, also emissions in sugarcane ethanol production must be addressed. In this area, there are two issues to be considered. Atmospheric emissions from sugarcane burning before harvesting and those from bagasse burned in boilers for cogeneration.

The sugarcane burning before harvesting practice was introduced in Brazilian sugarcane fields after the 1950s, aiming at higher productivity of the sugar cutter workers [40]. This practice eliminates the leaves of the sugar cane cleaning the way to proceed with the manual or mechanic harvesting. By doing this, up to 90% of undesirable vegetal matter can be removed from the harvesting feedstock [40]. Another reason for the burning is to avoid accidents with poisonous snakes and spiders.

However, there are serious drawbacks such as damaging the tissue of sugarcane and disturbing the soil structure enhancing the possibility of soil erosion [41]. Besides, there is an increase of pollutants such as particulate matter, carbon monoxide, and methane; locally it can increase the troposphere ozone concentration. Yet, there are several implications to the industrial phase like difficulties in the purification, need for faster utilization of the feedstock due to the shorter period for exteriorization [40].

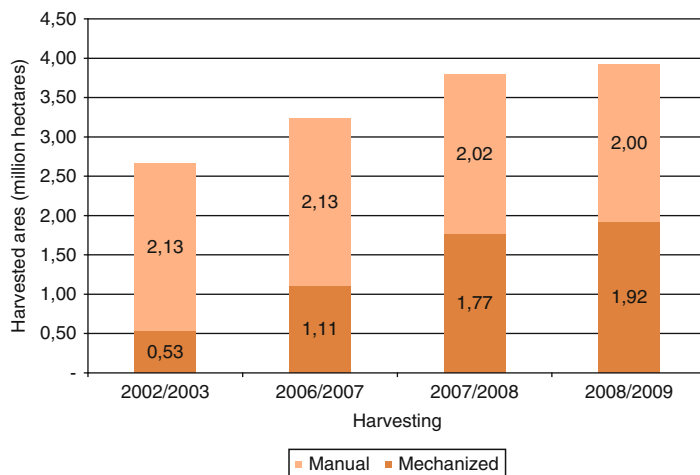
It is important to emphasize that elimination of the burning practice raises the energy balance of the sugarcane, which means more energy is produced. Even though the burning is a controlled fire in a delimited area with maximum duration of 10 min [12], it might represent risks to the grid cables, roads, and highway. On one hand, harvesting manually the green cane is possible, but the celluloid leaves can hurt if no protection equipment is used. On the other hand, sugarcane burning enhances the level of organic compounds, particulate matter, and methane.

Recently, environmental legislation enforces the phasing out of sugarcane burning in the State of São Paulo (State Law 11.241; see Fig. 4). Further on, the so-called Green Protocol was signed. This protocol is a voluntarily one, signed between the Government of São Paulo State, through its Environmental Secretariat and its Secretariat for the Agriculture, together with the Sugarcane Agroindustrial Sector of São Paulo State,

reducing the timetable for the elimination of the burning process. The Green Protocol anticipated the timetable for elimination of sugarcane burning in the state from 2021 to 2014, as well as, increased the percentage of green cane harvesting from 50% to 70% in 2010, for soils with slope until 12%. In the case of slopes that are higher than 12%, the elimination of sugarcane burning was anticipated from 2031 to 2017 and it also intends to increase the harvesting of green cane from 10% to 30% in 2010. In many other states, the local environmental agencies are also requiring the harvesting of green cane as one of the exigencies for the environmental licensing.

Therefore, in the State of São Paulo, in the crop season of 2008/09, 49% of the cane was harvested mechanically [42] (Fig. 4). It is important to remind that 80% of the sugarcane produced in Brazil is from the Center-South producing region where the State of São Paulo is located.

Regarding the burning of bagasse in boilers for cogeneration, despite the advantages of this process for the industrial productivity of sugarcane ethanol, there are pollutant emissions to be controlled. Even considering that there is no sulfur in biomass (i.e., no SO₂-emissions), emissions of particulate matter and NO_x must be controlled. There is also an adequate environmental legislation in the country to do so. Therefore, there are now limits for emissions (particulate matter and NO_x) from such equipment [43].



Bioethanol from Sugar: The Brazilian Experience. Figure 4

Evolution of mechanical harvesting in the state of São Paulo. (Law 11, 241/2002) [42]

Economic Aspects

In response to environment issues, marketing forces took place increasing the demand for biofuels. This is especially true when the oil price is high [44]. The producers as suppliers act in a market-oriented way following the demand and tending to seek for more productivity.

Sugarcane Ethanol Production Costs Analyzing the inputs that are part of the production costs of biofuels, it can be noted that fertilizers, feedstock, and energy consumption are important indicators. In the case of sugarcane ethanol, the feedstock (sugarcane) represents the highest share of the final production cost.

Considering the overall process, the ethanol price can be up to 70% of gasoline prices, ranging from US \$0.18 to 0.25 per liter. This is the lowest production cost of biofuels in the world.

An analysis of the investment costs for plant with processing capacity of two million tons of sugarcane a year shows that it would be necessary an initial investment of around US\$60 million, in 2005 prices [45]. Assuming the plant to be a regular mill, located in the Center-South of Brazil, the yield would be on average 79.39 l of anhydrous ethanol or 82.86 l of hydrous per ton of sugarcane. And one ton of sugarcane would cost US\$11.4. Without computing the interest for a plant with a lifetime of 25 years would result in a cost of US \$0.143 per liter of ethanol and an investment cost of about US\$ 0.017 per liter of ethanol produced.

The learning curve showed in Fig. 2 illustrates the competitiveness of Brazilian ethanol with gasoline in the international market. Other sugarcane producer countries have potential to implement biofuel program following the production costs reduction achieved by Brazilian experience with biofuels.

It is important to note that nowadays there are no subsidies paid in the country, only special tariffs for ethanol when compared to gasoline.

Brazilian Taxes Associated to Ethanol By the end of the 1990s, ethanol subsidies have been removed by the government and, since then, there is no price control from the government [2]. The deregulation of the ethanol market began during the Real Plan, in 1994, with the reduction of tax discount on Federal Excise

Tax on Industrialized Products (IPI) for new vehicles powered by ethanol and also reduction of price difference between gasoline and ethanol [46].

Nowadays, the only incentives in place are allocated in the acquisition of new vehicles on IPI and in the Tax on the Circulation of Goods (ICMS). Among the States, the lowest ICMS is in the State of São Paulo (12%) and highest is in the State of Pará (30%), the average being 24% [37]. Flex fuel vehicles or vehicles powered by ethanol have lower IPI (Federal Tax for Industrialized Products) than gasoline ones (Table 1).

Actually, a higher IPI levy on vehicles powered with fuels which have higher emissions of pollutants is a way

Bioethanol from Sugar: The Brazilian Experience.

Table 1 Taxes according to the fuel and vehicle type

Tax burden on new vehicles		
Type of vehicle	Federal tax IPI [47, 48]*	
Gasohol vehicles (running on gasoline – anhydrous ethanol blends)	7–25%	
Ethanol vehicles	7–18%	
Flex fuel vehicles (running on any blend of gasoline/alcohol)	7–18%	
Tax burden on fuels		
	ICMS** (range)	CIDE tax [12]***
Gasoline	25–31%	R\$ 501.10/m ³
Diesel oil	12–17%	R\$ 154.80/m ³
Natural gas	12%–	Zero
Hydrated ethanol	12–30%	R\$ 22.54/m ³
Anhydrous ethanol (levy on gasohol)	–	–

*IPI – Federal tax where the levy varies according to the engine that ranges from 1,000 to 3,000 cm³

**ICMS – State tax and is lower for ethanol. These taxes take into account the environmental benefits of alcohol. In the case of anhydrous ethanol (blended with gasoline), there is no state tax (ICMS); this tax is included in the final blend (gasohol). The tax varies according to the State

***CIDE (Contribution for Intervention in Economic Domain), a Federal tax established in 2002 for liquid/gaseous fuels. CIDE was created aiming to get funds for road conservation in the country and establishes differentiated values according to each fuel

of internalizing the costs of externalities caused by them. The structure of ethanol taxes burden can be described in a simplified way [12] as:

- At industry level, on the ethanol anhydrous and hydrated, the PIS/Cofins levy is 3.65%, on the revenue after the ethanol sales.
- Considering retailer, the so-called PIS/Cofins levy is 8.2% in the revenue from sales of ethanol hydrated by the retailer. In case of anhydrous ethanol, this fuel is blended with gasoline, thus the levy evenly to gasoline.
- In terms of State tax, the ICMS (Tax on the Circulation of Goods) is a state tax on industry and retailer and for ethanol, it ranges from 12% to 30%.

PIS and Cofins are concerned to social security, being PIS the acronym for Program for Social Integration contribution and Cofins the acronym for Contribution for the Financing of Social Security. Cofins is an additional contribution to finance social security based on the gross turnover of the company.

Social Aspects of Sugarcane Ethanol Production

Biofuels production generates significant social benefits for the developing countries, like economic growth and decrease of unemployment rate for people with low years of schooling in rural areas, through the creation of jobs in such areas.

Also the investment needed to create these jobs is much lower in biofuels sector than in others. In Brazil,

one job position creation in ethanol agro industry costs about US\$11,000 and for petrochemical industry the cost is 20 times more [49]. Figure 5 shows capital investment for job creation in different production areas and the quantity of job per unit of energy produced.

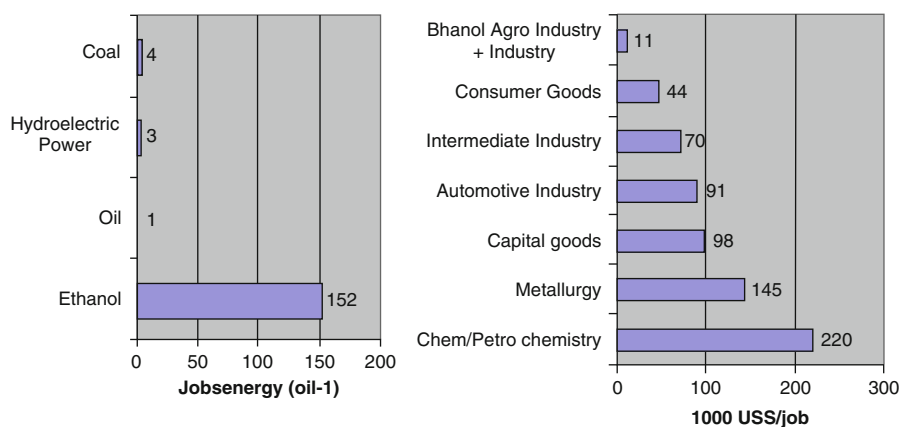
Another important aspect of social situation in sugarcane sector is related to the quality of jobs created. The evolution of the poor people income share of participation on GDP is shown in Table 2. There, not only an increase of this participation can be seen, but also an increase in the number of poor people.

The social inequality of rural areas in Brazil has not been improving significantly in the recent years. This fact is confirmed by the Gini index shown in the Table 3.

Normally, the agricultural sector presents many informal jobs, that is, the worker is not included in the national social security system. However, regions with sugarcane production in general present better social situation.

In 1992, the formal employment exhibited a rate of 53.6% that improved to 72.9% now. Taking into account the regional differences in the country, it can be seen that, in the State of São Paulo, formal employment rate in the sugarcane industry is 93.8%, whereas in the North/Northeast region, it is only 60.8%.

Regarding wages, in the Center-South production region, people working with sugarcane earn more than those working with coffee, citrus, and corn, but less



Bioethanol from Sugar: The Brazilian Experience. Figure 5
Jobs per energy and capital investment per job [49]

Bioethanol from Sugar: The Brazilian Experience. Table 2 Income share

	1999	2000	2001	2002	2003	2004
Share of income of the 50% Poorest*	12.69	–	12.58	12.98	13.36	3.85
Share of income of the 10% Poorest**	47.27	–	47.44	47.02	46.10	45.31
GDP per capita***	9,873	10,152	10,134	10,179	10,087	10,433
Number of poor people**** (million)	56.18	–	58.34	57.48	–	59.43

*This is the share of total income of the 50% poorest individuals, according to the per capita household income

**This is the share of total income of the 10% poorest individuals, according to the per capita household income

*** 2005 Reais

**** Number of people in households with per capita income below the poverty line

Source: Reference [50].

Bioethanol from Sugar: The Brazilian Experience.

Table 3 Gini indicator

Brazil	2003	2004	2005	2006	2007
Gini indicator for rural areas	0.5307	0.5166	0.5042	0.5003	0.5120

Source: Reference [50].

than those working with soybeans because this work is highly mechanized requiring more specialized workers. In the Northeast, people working in sugarcane crops earn more than those working in coffee, rice, banana, manioc (cassava), and corn crops, being their income approximately equivalent to the ones working in citrus, but lower than those ones working for soybeans. In fact, the enforcement of labor regulations in some regions of the country could indeed be improved, aiming to achieve the same situation already existing in several sugarcane regions.

Temporary migration of rural workers during the crop season occurs because the place where they come from does not offer many job opportunities. Usually, the profile of rural worker in the sugarcane crop is described as male, young (under 30 years old), with low level of education, and migrant from other region [51]. The labor journey of rural field workers according to the law is 8 h a day with a 1 h break for lunch. Considering rural workers in the sugarcane crop, in 2004, the number of workers was 493,162 and about 50% were seasonal workers [52]. Table 4 shows the educational level of several workers categories in the

sugarcane production in the State of São Paulo. This table shows that the category holding the lowest educational level is the rural field workers (sugarcane cutters).

Manual Harvesting of Sugarcane Crops Manual harvesting of sugarcane is an old practice in every country producing sugarcane and the main problem is the working conditions. In order to facilitate the work and prevent accidents with poisonous spiders and snakes, it is a regular procedure to burn the leaves of sugarcane. Usually, sugarcane harvested manually occupies ten workers per hectare [53].

Considering the legislation related to work conditions, Brazilian Labor Law is strict with regulation, but there are exceptions. Thus, there is a need for more law enforcement, in order to reach welfare to all rural workers.

Regarding government social assistance to rural worker in Brazil, the latest social governmental program is “Fome Zero” (Zero Hunger) including initiatives like “Bolsa Família” (Family Allowance), an aid to rural family ensuring minimum price for their crop, taxes reduction on basic nutrition items. These are government tools of redistribution [54]; other instruments that can be associated to the rural worker are the minimum wage and the national social security system.

Mechanization of Sugarcane Harvesting Mechanization of the agriculture is a process that has been taking place all over the world. Similarly to the industrial revolution, in the mid 18th Century, man work

Bioethanol from Sugar: The Brazilian Experience. Table 4 Job distribution per educational level, State of São Paulo

Occupations (%)	Tractor driver and machine operators	Supervisors	Sugarcane cutters	Other agricultural occupations	Other non- agricultural occupations
Illiterate	0.1	0.7	3.7	2.5	0.5
Incomplete 4th grade education	8.5	16.3	31.7	34	7.2
Complete 4th grade education	19.4	19.7	26.7	25.4	15.8
Incomplete 8th grade education	22.1	19.6	20.2	14.7	16.4
Complete 8th grade education	21.3	15	10	18.2	15.6
Incomplete secondary education	8.1	5	3.3	2.2	7.9
Complete secondary education	20.1	21.4	4.2	2.9	31.6
Incomplete higher education	0.3	0.6	0.1	0.1	1.8
Complete higher education	0.2	1.8	0	0	3.3

Source: Reference [37].

was replaced by machines, and this trend is also observed in the agricultural sector in Brazil. The mechanization process is happening not only in sugarcane crops, but also in other agricultural cultures, as well as, in other countries [55].

Since the beginning, the mechanization process has not been uniformly developed in Brazil, exhibiting distinct levels of mechanization depending on the region and on the type of crop [56]. In this way, the mechanization process for some agricultural crops is deemed partial due to the fact that harvesting process continued to be manual; one example is sugarcane crops that require a number of workmen for harvesting tasks.

The mechanization of the planting phase process has already changed the work relation and contributed to deteriorate the rural work quality giving raise to seasonal job. After the introduction of the legislation for the mechanization of the sugarcane harvesting, the mills have been investing in capacity building for the

rural workers aiming to develop more skilled people able to manage the mechanical harvesting machines, quite sophisticated equipment with computerized systems.

Seasonal Work Despite ethanol from sugarcane, rural field workers' condition is a subject of criticism, particularly the seasonal work. This sector holds the second highest seasonality in the country of 5.35 [57]. There is argumentation that seasonal job was a tendency of the agriculture [58].

Another reason pointed out was the agricultural modernization policy that was not favorable to small producers, who were not prepared either to production competition or work in the urban centers becoming seasonal workers [59]. Sometimes it is argued [60, 61] that the Federal Law N 4.214 from 1963, creating the Statute of the Rural Worker that extended to rural workers the same rights of the urban ones, has sped up the mechanization process.

In the State of São Paulo, the legislation goes beyond mechanizable areas with the recent legislation, Law N 11.241, of 2002. In order to follow the requirements of the legislation, the producers rapidly embrace mechanical power, but the level of mechanization depends upon availability of capital for investment.

As Brazil is a big country with regional differences, it is possible that part of the harvesting will continue to be manual, for some time, following the legislation schedule.

The alternative of harvesting with machines might cause unemployment of rural workers with low level of education that, possibly, will have difficulties to fit in the labor market. Regarding the sugar cutter unemployment, the legislation intends to tackle this problem including qualification of rural workers involving the partnership of unions. According to UNICA [62], with the effort of the associated companies, it is possible to improve the skills (qualification) of 7,000 workers a year.

The State of the Art on Sugarcane Ethanol

In the last 30 years, many technological improvements happened in ethanol field in agricultural and industrial production, in logistics and in the end users [63]. To do so, it was necessary to give subsidies at the initial stage, initiate negotiation among the sectors involved, and pass specific legislation [64] to open a window of opportunities and attract investments.

This topic will describe the state of the art of the fleet compatibility with ethanol, cogeneration process, technological development achieved, and logistic.

Compatibility of the Existing Fleet with Ethanol

This topic reports technological issues related to compatibility of the fleet with ethanol. Starting with the effect of ethanol on regular gasoline engine fleets, it then describes technological aspects of ethanol engine fleets and finally the new flex fuel engines.

Generally, the use of ethanol raises concerns about the compatibility of the regular existing fleet, as well as, the higher fuel consumption, since ethanol has lower energy content than gasoline.

The consumption drawback is partly compensated by the higher compression ratio that gives higher

efficiency to the fuel. Regarding regular fleet compatibility, the concerns rely on drivability, cold start, and damages of components of the vehicle. The losses in drivability may arise due to different ratio air/fuel for the combustion while cold start difficulties are caused by the lower vapor pressure. Most of the worries are the chemical attack in plastic and rubber materials of vehicle and corrosion of metallic materials of vehicle. Notwithstanding, the occurrence of these events aforementioned depends upon the amount of ethanol blended with the gasoline, the vehicle age (reflecting its technological level), and the ethanol fuel specification and quality [45].

Furthermore, small blends of ethanol with gasoline up to 5% are acknowledged as inoffensive to the regular fleet. The World Wide Fuel Charter [65] establishes maximum oxygen content in gasoline of 2.7% m/m, that is, blends higher than 5% are allowed by this specification. Many countries have introduced low concentration of ethanol blended with gasoline (up to 10%) as regular fuel for vehicles developed for neat gasoline without significant performance loss. In case of vehicles with electronic fuel injection (EFI System), this device enables automatic correction of the engine air/fuel ratio. Ethanol blended with gasoline presents a relatively low consumption increase of less than 3%. Table 5 [66] displays the necessary adjustments in vehicles for the use of national sugarcane ethanol blends.

Cogeneration in Sugarcane Mills

Cogeneration process is the simultaneous electric/mechanical and thermal energy production from the same energy source. In the case of Brazilian sugar/ethanol mills, the source of energy is sugarcane bagasse.

Until the late 1990s, sugarcane bagasse was deemed an undesirable waste by the sector and was inefficiently burned or traded. Later on, the situation started to modify due to the need of changing the old boilers with 20 years in the edge of their life cycle. Some mills started to introduce more efficient boilers (higher-pressure boilers, up to 80 bar, instead of the old ones working with 21 bar) [4]. Step by step, other mills also became interested on this technology and the improvements started to happen.

Associated to this fact, another action that propelled the technological upgrade was the Program for

Bioethanol from Sugar: The Brazilian Experience. Table 5 Fleet adjustment to run ethanol

Ethanol content in the fuel	Carburetor	Fuel injection	Fuel pump	Fuel pressure	Fuel filter	Ignition system	Evaporative system	Fuel tank	Catalytic converter	Basic engine	Motor oil	Intake manifold	Exhaust system	Cold start system
≤5%	NN for any vehicle													
5–10%	PN	NN for relatively new fleets (10–15 years old)												
10–25%	PN, Brazilian application									NN				
25–85%	PN, US application													
≥85%	PN, Brazilian application													
	NN													

Modifications: (not necessary – NN – and possibly necessary PN) in vehicles for different ethanol blends
Source: Reference [66].

Alternative Electric Generation Sources and Wind Energy (PROINFA) that was a political incentive to energy generated from renewable sources. In the case of biomass, where sugarcane bagasse cogeneration is included, the electricity surplus sold to the grid relies on several aspects, such as the type of cogeneration technology used, the quantity of steam consumed to produce sugar and/or ethanol, and the amount of bagasse available [64].

In 2007, the total electrical energy sold in the market was about 900 MW, and nowadays, it is 1,000 MW. The plants work in a complementary basis with the hydroelectric system, since the plants are operating at full power in the dry season in the Center-South. In fact, there are still several opportunities for enhancing the power generation if all the plants are modernized and the use of tops and leaves (trash) of the sugarcane is introduced with the mechanization of green cane.

PROINFA was created by the Law N 10438, 2002, that established that 3,000 MW would be purchased from renewable energy sources, specially wind, small hydro, and biomass. In the case of biomass, actually the price and long-term contracts (20 years), established for electricity purchase, were not considered attractive to make all the mills modernize to produce surplus of electricity. Therefore, the limit of 1,000 MW was not achieved by biomass and the share of power not bought from biomass was transferred to wind and small hydro sources of energy.

Actually, most mills prefer to send their electricity surplus to the utilities in short term contracts. Besides that, also the grid connection is still a barrier that needs to be overcome; by the time this entry was written, many mills were developing special agreements in order to allow the construction of transmission lines from the plant until the grid (see also [65]).

Technological Development

In Brazilian experience of producing ethanol, three technological phases can be identified [37]. In the first phase, from 1975 to 1985, the focus was on productivity to supply the growing demand. This phase was characterized by the search for higher milling capacity, improvements of distillation systems,

fermentation productivity gains, and agricultural productivity increase.

Since the production was stabilized, as of 1980, the emphases shifted to better conversion efficiency such as higher efficiency of the extraction and fermentation phase. In the mid-1980s, there was more attention in technological tools for agro-industrial production management like optimization and renovation of sugarcane plantations in order to monitor the harvest, control the operational processes, and control simultaneously agriculture and industry. The development was not homogeneous, and the three phases can still be found. Comparing the maximum conversion efficiency to the average values, 10% difference could be found between the production units, but growing over the time indicating large internal technology transfer.

The most relevant information about the technological development is summarized in Box 3. According to this, the Brazilian technological level for ethanol fuel production is deemed the best in the world (as proven by the production costs and the conversion efficiencies). In the sugarcane research area, Brazil shows the largest number of technical publications [64].

Box 3: Technological Development

Period of 1980–1990: Large-scale introduction of sugarcane varieties developed in Brazil (mainly by CTC-Copersucar and Planalsucar programs); development of the full use of the sugarcane stillage in fertirrigation; biological controls in sugarcane production; development of the milling system with four cylinders; power production in the industry (self-sufficiency); end use; ethanol specifications; ethanol engines, ethanol transportation, blending and storage.

Period of 1990–2000: Optimization in sugarcane cutting, loading and conveyance; sugarcane genome mapping; genetic transformations, harvesting mechanization, achievement of electric power supply and their selling to the grid; advancements in industrial automatization; enhancement in technological management (both industrial and agricultural); introduction of flex fuel engines.

Source: Reference [63].

Logistics

The production of biofuels requires the existence or development of a support structure to collect the biomass, transport it to the industrial plant to be processed, and to distribute the biofuel. This is an important issue when the perspective of replication the Brazilian experience is being discussed, as is happening nowadays.

In addition to the requirements mentioned above, there is also the need for appropriate facilities for storage. The logistical structure of biofuels is complex and involves local, regional, and long distance transportation, delivering the product to other consumer centers or even to export. Depending on market destination of the ethanol (internal or exportation), the logistic must be handled separately.

If the final destination is the internal market, the production must be delivered to a fuel distribution base because of legal reasons; however, if the production is going to be exported, the commercialization can be developed directly from production plant or fuel distribution base [67]. Regarding the storage facilities, the storage might be done either by the producer storing the production surplus in tanks inside the industry or by the retailer in the terminals to guarantee the supply in short term [41].

Brazil has a logistic structure consolidated and well distributed for hydrated ethanol or anhydrous ethanol blended with gasoline, where both types of ethanol hydrous and anhydrous are transported via road, rail, and pipelines [68].

At long term, the infrastructure of storage capacity does not seem to be a limiting factor. In 2007, there were 273 retailer spread around all the states of the country with storage capacity of 3.75 million cubic meters [41]. Unlikely the storage, the infrastructure of ethanol transportation regarding the growing production seems to be a bottleneck for developing countries with a lack of local infrastructure.

International Dimensions of the Ethanol Program

Ethanol Programs in Other Countries

Several countries have already started biofuel programs. The most important one existing today (and also the largest one) is the US ethanol program,

producing ethanol from corn. The current production of corn ethanol by the USA reaches 41 billion liters [69].

The 2007 US Energy Bill set a target of producing 15 billion gallons (56.8 billion liters) of ethanol a year from corn by 2015, using first-generation technologies, which will probably require an agricultural area of approximately 14 million hectares. Further expansion of production is planned, up to 21 billion gallons (79.5 billion liters) a year, using cellulosic materials and second-generation technologies that are still in experimental phase.

Another policy pointing in this direction is the European Union directive, which will require 3.9 billion gallons per year by 2020 in order to replace 10% of the gasoline for internal consumption. At the present, their production is two billion liters a year. Production of ethanol from corn, using first-generation technologies, will be at least 87.8 billion liters a year in 2015, up from 36.8 billion in 2006.

There is an important difference between the production of ethanol from sugarcane in Brazil or from corn in the USA, and from starch feedstock in Europe. The difference between them relies on industrial processes that require external sources of energy like oil or gas to supply electricity and heat.

In practical terms, in USA and European Union (E.U.), ethanol is obtained partly by burning coal (the main source of energy in the region) to produce the energy necessary to the processes inside the distilleries. Unlike USA and E.U., in Brazil, the use of sugarcane bagasse as feedstock makes far better energy usage avoiding fossil fuel consumption. This is possible due to energy content in the feedstock. The concept of energy balance used to evaluate the use of fossil fuels in preparing ethanol was already discussed in the Sect. “From Field to Motor”.

Many studies have been conducted on this subject, and the results are sensitive to assumptions about the use of fertilizers, pesticides, and other energy inputs. According to one estimation compared to gasoline, ethanol from corn emits 30% less CO₂ and ethanol from sugarcane 82% less [70].

In the USA, efforts to expand ethanol production from corn face severe obstacles. The amount of corn directed to ethanol production is already 18% of the production, spread in a total area of 37 million

hectares. The increase in corn-planted area has been made at the expense of soybean-planted area. Production of ethanol from cellulosic materials, which could be a solution, is still facing technological problems that are not likely to be solved by 2015. Nevertheless, productivity increases including genetic modification might represent a significant reduction in the amount of additional land necessary.

This large demand for ethanol and the corresponding use of agricultural land to produce it have generated a number of objections to the use of biofuels. Some argue that the competition between land for fuel (ethanol) and land for food, in both the USA and Europe, is causing famine around the world and leading indirectly to deforestation in the Amazon and other tropical areas [31, 32]. The recent rise in the prices of agricultural products, after several decades of declining real prices, is often seen as a cause of famine, and led to the politically laden debate of fuel versus food. All together, the grain prices have more than doubled since January 2006, with over 60% of the rise happening since January 2008. It was closely following the price of petroleum that started to diminish when 2008 crop was harvested. In contrast, the point has been made that higher crop prices will not necessarily harm the poorest people because many of the world's 800 million undernourished people are farmers or farm labors, who could benefit from higher prices.

More recently, the price of agricultural products has decreased following the decline in petroleum prices. To keep the issue in perspective, it is important to remember several facts. First, around the world, 93 million hectares are currently being used to grow soybeans and 148 million hectares for corn, while the amount used in the USA to produce ethanol is approximately seven million hectares. Second, in general, the prices of food commodities have been decreasing since 1975, but fluctuations frequently occur in those prices, as well as, in the areas planted and the prices of crude oil. Those fluctuations, which have occurred for decades, result from many factors and events [64] and not due to biofuels expansion.

Worldwide, 1.5 billion hectares of the arable land is already being used for agriculture and another 440 million hectares is potentially available, including 250 million hectares in Latin America and 180 million in Africa. As such, the area currently being used for

biofuels is only 0.55% of the land in use. This expansion has been extensively analyzed in many reports (e.g., [34]) which pointed out that several individual factors have driven up grain prices and in combination led to an upward price spiral. Among them are high energy and fertilizer prices, the continuing depreciation of the US dollar, drought in Australia, growing global demand for grains (particularly in China), changes in some nations' import-export policies, speculative activity on future commodities trading, and regional problems driven by subsidies of biofuel production in the USA and E.U.

One example is the land changes in the USA in the period 2006–2007, corn acreage grew 19% utilizing nearly 37 million hectares, an increase of 7 million hectares. Most of this expansion came at the expense of soybean acreage, which decreased by 17%, from 31 to 26 million hectares (i.e., 5 million hectares). This is approximately 6% of the world's area used for that crop, and that change is helping to drive up prices.

Because of this land changes, other countries had to expand their soybean production, possibly increasing deforestation in Amazon. Such speculations about a *domino effect* are not borne out by the facts since the area used for soybeans in Brazil (mainly in Amazon) has not increased from 2004 onward. The deforestation in the Amazon rain forest has been going on for a long time at a rate of approximately one million hectares per year [71], and recent increases are not due to soybean expansion but due to cattle and are inconsistently related to ethanol production [35].

Replicating the Brazilian Experience Elsewhere

Almost 100 countries are producing sugarcane over an area of 20 million hectares and the fifteen most important producers hold 86% of the sugarcane production. And the conversion of sugar plants into ethanol distilleries is relatively easy, and most of the existing plants in Brazil have these dual purposes. Taking advantage of the easy reversibility of the production units, the ethanol production in other countries could be significantly expanded following the Brazilian experience with ethanol, using a fraction of their sugarcane for ethanol.

The question that arises is: Why are other sugarcane-producing countries not using some of their raw material to produce ethanol? One, it could be export to the

Bioethanol from Sugar: The Brazilian Experience.**Table 6** Subsidies for biofuels in the USA and E.U., 2006

	Ethanol			Biodiesel		
	Total, in US\$ billions	Billions of liters	US \$/l	Total, in US\$ billions	Billions of liters	US \$/l
US	5.8	20.7	0.28	0.53	0.96	0.55
EU	1.6	1.6	1	3.1	4.43	0.70
Total	7.4	22.3	–	3.63	5.39	–

Source: Reference [72].

USA and E.U., where production costs are significantly higher. The main reason is the high import duties imposed on ethanol imports in the USA and E.U. to protect local industries, which are heavily subsidized. Table 6 displays an estimation of the subsidies in the USA and E.U., which totaled almost \$12 billion in 2006.

Removing these subsidies is a topic of discussion in the Doha round of negotiations, but prospects for progress in this area are poor (Box 4). Several countries in Central America benefit from their privileged access to the US market. The members of the Caribbean Basin Initiative (CBI), the oldest group, up to 7% of the previous year's US ethanol demand is exempt from import tariffs [2, 73].

This agreement has been used mostly to allow these countries to import dehydrated Brazilian ethanol. In the past, European hydrous ethanol was also included. Dehydration plants are located in Costa Rica, the Dominican Republic, Trinidad and Tobago, El Salvador and Jamaica. The USA imported 482 million liters from these countries in 2006 and 877 million liters in 2007, considerably less than the 1.3 billion liters that the 7% limit represents on ethanol imported from Caribbean countries. The Central America Free Trade Agreement (CAFTA), signed in August 2004, immediately eliminated all tariffs and quantitative restrictions on 80% of manufactured goods in that market, including ethanol, with the remainder phased out over a few years. Nearly all of the 6 nations in CAFTA have already initiated plans to develop large-scale ethanol production. El Salvador is the most advanced, since it has already

Box 4: Biofuels and the World Trade Organization

Nowadays, the World Trade Organization (WTO) does not have a specific trade regime for biofuels. Therefore, international trade in biofuels falls under the rules of the General Agreement on Tariffs and Trade (GATT, 1994), which covers trade in all goods, as well as, other relevant WTO agreements such as those on agriculture, technical barriers to trade, the application of sanitary and phytosanitary measures, and subsidies and countervailing measures. Agricultural products are subject to GATT and to the general rules of the WTO, insofar the Agreement on Agriculture (AoA) does not contain derogating provisions. Key trade-related issues include the classification for tariff purposes of biofuel products as agriculture, industrial, or environmental goods; the role of subsidies in increasing production; and the degree of consistency among various domestic measures and WTO standards. The AoA covers products from Chaps. 1 to 24 of the Harmonized System, with the exception of fish and fish products and the addition of many specific products, including hides and skins, silk, wool, cotton, flax, and modified starches. The discipline of the AoA is based on three pillars: market access, domestic subsidies, and export subsidies. One of its main features is that it allows members to pay subsidies in derogation from the Agreement on Subsidies and Countervailing Measures. The Harmonized System classification affects the way products are characterized under specific WTO agreements. In this classification, ethanol is deemed as an agricultural product being subject to Annex 1 of the AoA, whereas biodiesel is classified as an industrial product and is therefore not subject to the disciplines of the AoA. The paragraph 3 (iii) of the Doha Development Agenda displays negotiations on "the reduction or, as appropriate, elimination of tariff and non-tariff barriers to environmental goods and services." Some WTO members have suggested that renewable energy products, including ethanol and biodiesel, should be classified as "environmental goods" and therefore subject to negotiations under the "Environmental Goods and Services" cluster.

Sources: References [76–78].

drafted legislation to continue developing a local ethanol market and is beginning to invest in ethanol production. An old distillery that can produce 60 million liters a year is being revamped to double its capacity and is already exporting all its production. Similar initiatives are underway in Guatemala and Costa Rica [74].

Across the Atlantic, two key elements of the E.U. General System of Preferences are the *Everything but Arms* (EBA) initiative and the *Special Incentive Arrangement for Sustainable Development and Good Governance* (GSP+). EBA provides special treatment for fifty least-developed countries, giving duty-free access to imports of all products except arms and ammunition, without any restrictions on quantity, with the exception of rice and sugar up to October 2009. At present, GSP+ benefits 16 countries, mostly in Latin America and the Caribbean. Any GSP+ beneficiary country must be both “vulnerable,” according to a definition established in the regulation, and have ratified and effectively implemented 27 specified international conventions in the fields of human rights, core labor standards, sustainable development, and good governance. This program grants special duty-free access to the E.U. market for denatured or non-denatured alcohol [75]. In order to benefit from such

advantages, a few countries in Latin America and Africa are starting to divert some of their sugarcane to ethanol production and others, especially Venezuela, are expanding their sugarcane plantations. Regarding these issues, some recent reports from UNCTAD discuss on only certification issues and the impact on developing countries, as well as, the perspectives for second-generation technologies in these countries [2]. Table 7 provides a list of projects underway around the world.

This development represents a modernization of the sector which traditionally was in the hands of prosperous family groups that benefited from special relationships with the E.U. that let them sell sugar at far more than the international price. Their price was based on the much higher price of locally produced sugar from sugar beets or sweet sorghum. This comfortable situation discouraged them from entering into the ethanol business, which required additional investments and know-how.

Future Directions

If second-generation technologies do not materialize until 2022, most of the ethanol required in the USA will probably have to be imported from countries in the Southern Hemisphere, such as Brazil where the sustainable land expansion and good climate particularly favor its production from sugarcane.

In all likelihood, ethanol consumption, which represented 0.4 million barrels of oil equivalent per day in 2006 (1.2% of all gasoline in use in the world) will grow to 2.6 million barrels of oil equivalent per day in 2022, replacing 10% of all gasoline used in the world. Considering that current oil consumption is 85 million barrels a day and that it might grow to 100 million by 2012, ethanol would be contributing the equivalent of almost 3% of the world's consumption of oil. That is a significant amount and will help drive down the world price of petroleum.

Neither USA nor E.U. will be able to produce all the ethanol it needs; in all likelihood, they will have to import it from Brazil and other tropical sugarcane-producing countries. This could be a mutually beneficial solution, reducing the cost of fuel for consumers in the USA and E.U. and generating hundreds of thousands of jobs in the developing countries.

Bioethanol from Sugar: The Brazilian Experience.

Table 7 Projects under development

Country	Capacity (m ³ ethanol/day)	Status
Colombia	150 × 5	In operation
Venezuela	700 × 4	In construction
Angola	1,000	Firm proposal
Colombia	1,000	Firm proposal
Bolivia	500	Firm proposal
Paraguay	700	Firm proposal
Colombia	300 × 2	Firm proposal
Colombia	100	Firm proposal
Colombia	150	Firm proposal
Colombia	200	Firm proposal

Source: Olivério J, Vice President of Operations, Dedini Organization, personal communication.

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Biofuels and Sustainable Buildings

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Article Outline

Glossary
 Definition of the Subject and Its Importance
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Glossary

Alcohol A compound in which the –OH group is connected to an aliphatic carbon atom.

Biofuel General classification of a fuel refined from recently harvested organic matter.

Biomass The solid form of biofuel.

Biogas The gaseous form of biofuel.

Bioliqid The liquid form of biofuel, ethanol, and biodiesel.

Catalyst A substance that enables a chemical reaction to proceed at a usually faster rate or under different conditions (as at a lower temperature) than otherwise possible.

Cetane number A measure of the ignition quality of diesel fuel and influences combustion characteristics.

Feedstock The raw material that will be processed into a fuel.

Petrol-diesel Diesel fuel that is derived from petroleum.

Pour point The temperature at which a liquid stops behaving like a liquid.

Transesterification The process of converting one ester into another ester using an alcohol and oil.

Definition of the Subject and Its Importance

Biofuels come in many forms and from a variety of sources. The biofuels may be solid (biomass), gas (biogas), or in liquid form (biodiesel, ethanol, etc.). Biofuels may be derived from most plant material as well as some animal parts, typically animal fats. As plants grow over much of the world's landmass and their primary source of energy is the sun, biofuels are abundant and renewable. Furthermore, as biofuels absorb the sun's energy to grow, biofuels are nature's solar energy battery.

Biofuels have been used for thousands of years as a source of heat and light for civilization. However, as humanity's energy consumption has become more sophisticated, fossil fuels have gained a technological edge in refining and supply chain management. For the last decade, renewed interest in biofuels has increased the adoption of biofuels for making heat and electricity. The drivers for the interest in biofuels are many; including energy security, environmental concerns, and economic competitiveness.

To address all these interests, the entire life cycle of the biofuel and its use must be considered. Energy security or establishing an effective/reliable supply of biofuels is a must for any building operator considering biofuels as a primary fuel source. Pollution concerns may drive a building operator toward or away from biofuels. For example, soy-based biodiesel reduces particulate production in an engine generator; however, NO_x emissions may increase. Both particulates and NO_x are regulated emissions and a building operator will need to be aware of the implications of their fuel choices. Economic concerns are important for most building operators. A fuel source with a competitive/stable price is highly sought after. As recent history has shown, most fuels do not appear to be immune from macroeconomic price influences as was seen in gasoline and ethanol prices in the late 2000s.

Biofuels can be used to generate heat in boilers or both electricity and heat in engines, gas turbines, etc. Biomass in the form of wood pellets or chips are used with some frequency in residential and some commercial heating applications and a number of manufacturers of pellet and chip burning heating systems are on the market. Larger boilers may use biodiesel in place of fuel oil or biogas in place of natural gas to make larger quantities of heat.

Biofuels have also been used to make electricity and heat in power plants of a variety of sizes. Large amount of biomass such as sawdust are burned in boilers to make steam to drive a turbine, which in turn generates electricity. Smaller applications include using biodiesel, ethanol, and biogas in engine generators and gas turbines to provide backup power or primary power and heat. Similar to the wood chip and pellet burning, there are several manufacturers of engines and gas turbines that offer systems capable of using biofuels for building applications.

Introduction

Biofuels have been used for thousands of years to make heat and light; however, recent political, economic, environmental, and security concerns have refocused the world's attention on biofuels of all types.

The majority of attention is focused on biofuel for transportation purposes; however, as the U.S. Department of Energy has stated that, 40% of energy consumption and emissions come from building operations [1]. To alleviate the environmental impact of building operations, world governments, researchers, and building designers are looking for ways to reduce the carbon footprint of buildings as well as finding alternatives to dwindling supplies of fossil fuels required to operate modern buildings.

The building owner/operator should be aware of the entire life cycle of the selected biofuel to avoid any operational disruptions of embarrassment that may arise from a less efficient part of the biofuel delivery process. For example, high-quality palm oil may be very desirable for a boiler. However, if that palm oil comes from a plantation, where a rainforest once stood and was burned to the ground, the environmental benefit of that palm oil would be in doubt.

The life cycle of a biofuel is broken down into five parts, each of which has several considerations:

- Growth
 - How fast does the feedstock grow?
 - How much energy is derived per pound of plant material?
 - How much energy does it take to produce the plant material?
 - Where does the plant material grow?
 - What grew in this location before the biofuel crop?
- Harvest
 - What methods of harvesting the plant material are used?
 - Does the method of harvesting use more energy than the biofuel generates?
- Refining
 - Does the refining process generate large waste streams?
 - How much energy does the refinement process consume?
- Distribution
 - Does the shipping of the biofuel consume more energy than the biofuel generates?
- Use
 - How efficiently is the fuel being burned?
 - Is the fuel being burned cleanly to meet emissions standards?
 - Is the fuel being stored properly and safely?

The building owner/operator is most directly impacted by the “Distribution” and “Use” phases of the life cycle analysis, but as stated other parts of the life cycle may be significant to the user of the biofuels and undermine their broader sustainability goals.

Growth

Different sources of biofuels grow at varying rates, in varying conditions, with varying amounts of required resources. Needless to say, not all biofuels are created equally. For example, Fig. 1 shows the quantity of oil per unit area for many different types of crops. See reference for a more complete listing of plants.

While the actual input energy for growing an acre of crops varies depending on location and technology, it is clear that some crops are better than others for creating

Plant	Latin Name	kg Oil/hectare	lb Oil/acre
Corn	Zea Mays	145	129
Palm	Erythea Salvadorensis	189	168
Cotton	Gossypium Hirsutum	273	243
Soybean	Glycine Max	375	334
Pumpkin Seed	Cucurbita Pepo	449	400
Mustard	Brassica Alba	481	428
Sunflower	Helianthus Annuus	800	712
Peanut	Arachis Hypogaea	890	792
Opium Poppy	Papaver Somniferum	978	871
Rapeseed	Brassica Napus	1,000	890
Castor Bean	Ricinus Communis	1,188	1,058
Jatropha	Jatropha Curcas	1,590	1,416
Coconut	Cocos Nucifera	2,260	2,012
Buriti Palm	Mauritia Flexuosa	2,743	2,442
Macauba Palm	Acrocomia Aculeata	3,775	3,361
Oil Palm	Elaeis Guineensis	5,000	4,452

Biofuels and Sustainable Buildings. Figure 1

Average production rates of vegetable oils by plant type [2] (1 kg/ha \approx 0.9 lb/acre)

energy and the users of this energy should be aware of their impact. This same concept applies to biomass and biogas, where there can be great variability depending on the feedstock, which should be discussed with the fuel supplier.

Refining

Most of the processes to create biofuels are conceptually simple; however, the creation of high quality, certified biofuel typically requires specialized equipment and skilled personnel to carry out the process. The text below will outline the basic process for refining biofuels; however, the refinement steps required to make certified fuels are typically much more demanding.

Biomass

When using biomass as a primary energy source it is best to refine the fuel somewhat rather than just cutting down a tree and throwing it into a fire. Most biomass contains a significant amount of moisture, which reduces combustion efficiency and increases particulate and carbon monoxide pollution. As the moisture in the wood evaporates due to the heat from the fire, it displaces oxygen thus reducing the combustion efficiency, which is directly related to the amount of oxygen available. Therefore, wood is often dried prior to being supplied for use in commercial boilers.

In addition to drying the biomass, it is often pelletized or broken down into smaller pieces or chips. This simplifies distribution of the product and simplifies automatically feeding the biomass into boilers. Making smaller pieces of wood also aids the combustion process by making it easier for air to get to the fuel for burning cleanly.

There are many other types of biomass that have various refining methods, from sawdust at lumber mills to grass clippings and tree trimmings burned in an incinerator, but these are more customized systems. The wood chip or pellet burning boilers are the most common application of biomass fuel use in buildings.

Bioliquids

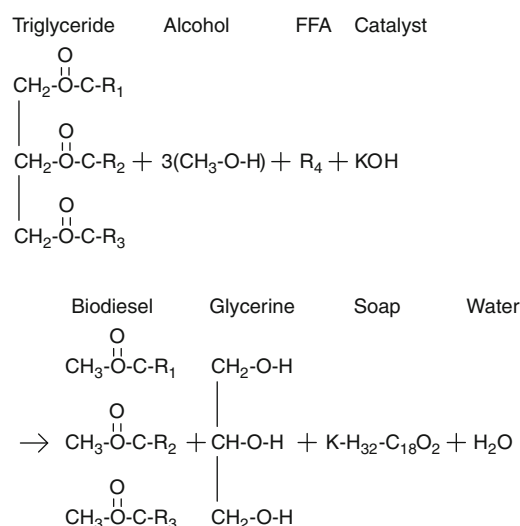
Bioliquids (biodiesel and ethanol) are more complex and require a basic knowledge of chemistry. Ethanol is made like any consumer alcohol through fermentation of sugars. Most commonly these sugars come from corn or sugar cane. The ethanol is then denatured to prevent the ethanol from being used in food products to avoid alcohol taxes which would significantly alter the price of ethanol.

Pure ethanol can be used directly in some engines; however, more commonly an 85% ethanol/15% gasoline mixture known as E85 is sold in the USA and can be used in vehicles with flex fuel engines. Flex fuel engines are defined as engines that can use multiple fuel types and grades. Currently, all modern vehicle engines sold in the USA can already accept up to 10% ethanol mixed in with the gasoline.

At this time there are no commercially available E85 boilers or generators; however, ethanol is the most common biofuel available in North America with its primary use for transportation.

Biodiesel is also mostly used for transportation purposes; however, more boiler and generator applications exist as it is more similar to standard Diesel fuel than E85 is to gasoline. Biodiesel is refined in a process known as transesterification. This process includes combining almost any vegetable oil or animal fat with an alcohol and a catalyst. The types of oils used are known as triglycerides, which are long-chain fatty acids joined by a glycerin backbone. Some of the most common alcohols used are ethanol, butanol, or methanol.

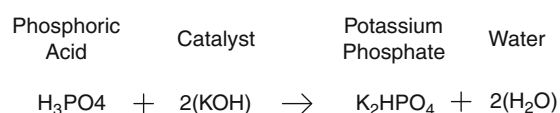
The catalyst, typically sodium hydroxide or potassium hydroxide, speeds up the reaction which separates the esters. The chemical equation below depicts the basic transesterification process.



Equation 1: Basic transesterification process [3]

The two most important effects of the transesterification process are to reduce the freezing temperature of the ester and to reduce the viscosity of the ester so it can be used over a wider range of temperatures. Some older diesel engines have been observed running on heated, unaltered vegetable oil; however, newer high-precision engines require higher grade fuels, which the transesterification process provides.

Once the transesterification process is complete, a neutralizing acid is added to the system to cause the potassium or sodium to precipitate, which simplifies the processes of removing it from the biodiesel. Furthermore, the biodiesel is washed with water to remove excess alcohol from the biodiesel.



Equation 2: Neutralizing step for the transesterification process

There are dozens of proprietary processes used commercially that have reduced the refining time and improved the yields of the refining process; however, that is beyond the scope of this entry.

Biogas

Biogas can often be found on farms, landfills, and wastewater treatment plants. The process is complex but primarily involves capturing, cleaning, and dehumidifying the methane gas that is generated from decomposing organic matter.

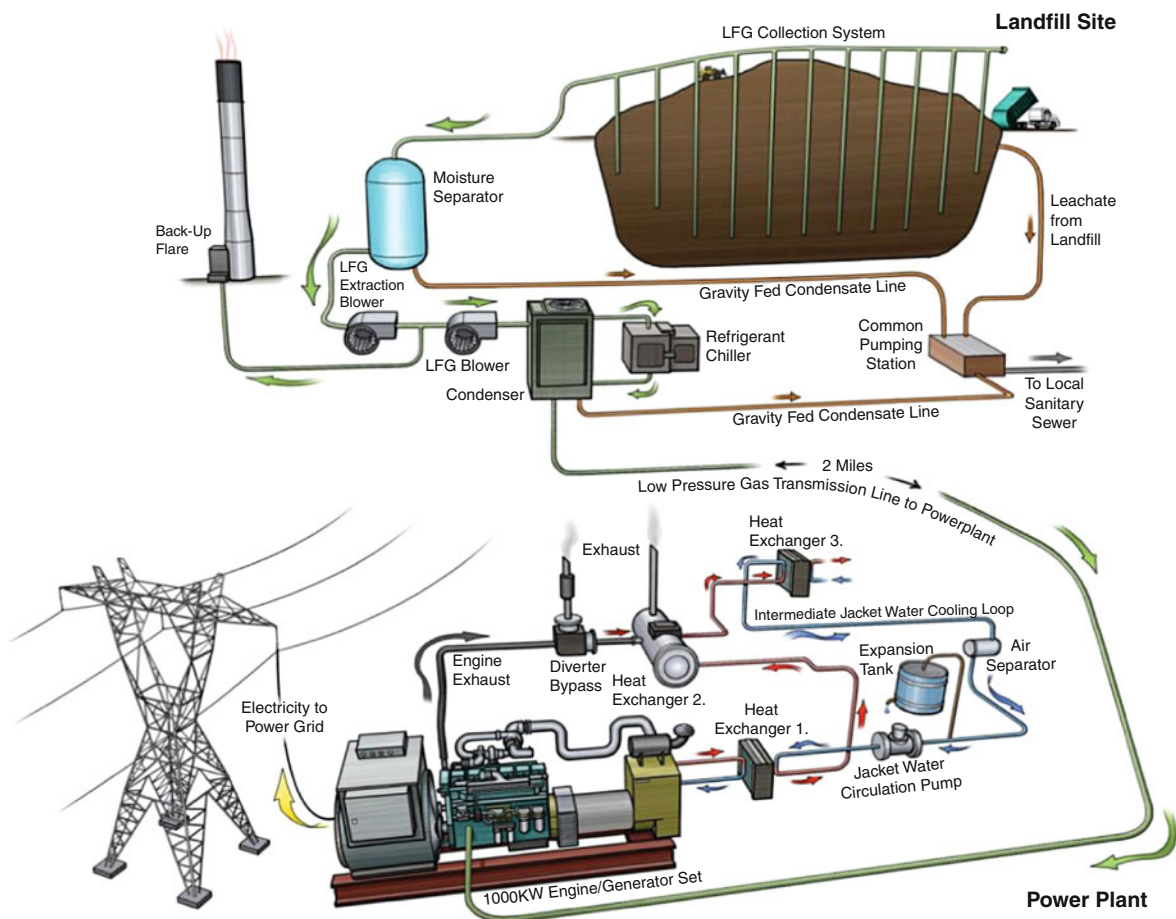
As methane is the primary component in biogas as well as natural gas, it can be considered a direct alternative if the biogas has been sufficiently refined. A large portion of the biogas refining process is removing siloxanes and moisture from the gas, which can cause engines and boilers to fail prematurely.

There are many commercially available boilers, engines, and gas turbines that will run off less refined biogas; however, there is a cost premium due to more

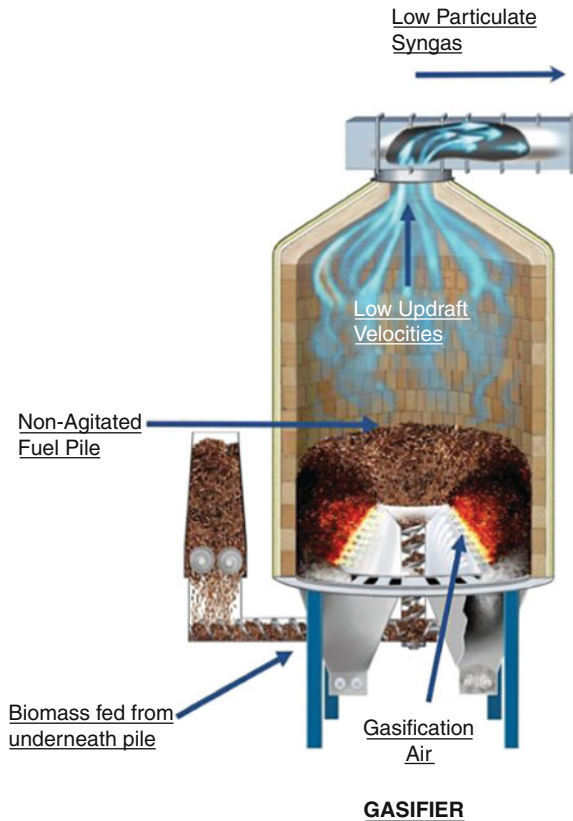
expensive materials. Therefore, a balance must be struck between refining and use.

Typically biogas refineries collect a significant amount of biomass such as municipal waste treatment facilities, landfills, and farms. It is difficult to justify the installation of such a system if little biomass is available. Working with the local gas company to find a supplier of biogas may be an alternative approach to supplying your building's systems with biogas. Figure 2 shows a system that is being constructed in 2011 to supply a university with biogas from a municipal landfill.

The system shown in Fig. 2 is being built in stages with the landfill flaring system being constructed first. The advantage of building the flaring system first is to determine how much gas is available before selecting



Biofuels and Sustainable Buildings. Figure 2
1 MWe landfill gas cogeneration system [4]



Biofuels and Sustainable Buildings. Figure 3
Biomass gasification system [5]

the pipeline and plant size. The quantity of gas production is very difficult to predict as the exact type of waste deposited in the landfill over the last 25 years is unknown.

An alternative system is a biomass gasification system that uses wood chips and process known as pyrolysis, which burns wood chips in an environment with little oxygen as shown in Fig. 3.

The balance of the biomass gasification system may use boilers or engines coupled with heat recovery, which will be addressed in later sections.

Owner/Operator Concerns

The day-to-day operations that effect building owners and operators include the supply, storage, use, emissions, and cost of the biofuel. As stated, the issues discussed in the background section should be of concern to the building owner in a holistic sense, the

following sections will describe some of the challenges and considerations that directly impact the building owner and operators as well as the design team.

Supply Chain

Establishing a steady supply chain for biofuels is of vital importance to the successful operation of any system. Unlike fossil fuel distribution infrastructure, biofuel distribution infrastructure is limited and may be unreliable in certain areas for certain fuel types. There is a growing body of trade associations for commercial biofuels that can assist building owners in establishing a steady supply chain [6–8].

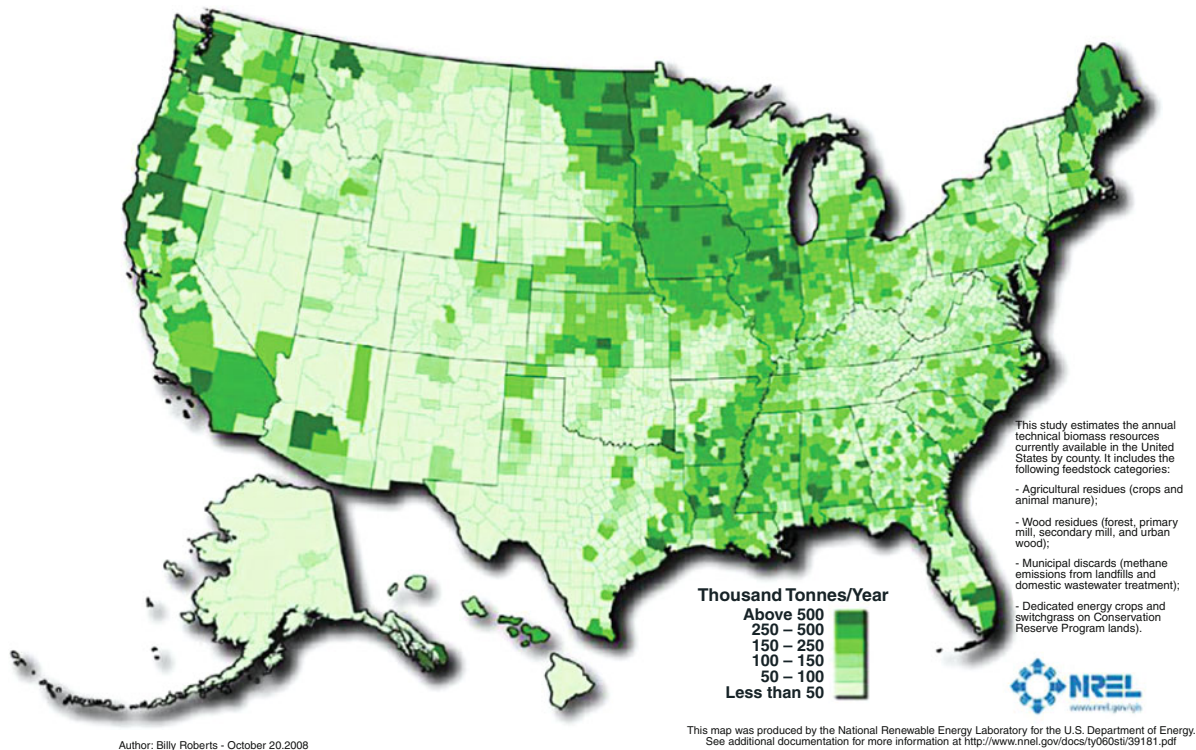
An alternative to commercial biofuel supply is to establish an independent biofuel infrastructure. Building designers and owners should be aware of nearby resources such as farms, waste treatment facilities, and/or cafeterias/restaurants that generate significant resources that could be converted into biofuels. While it is complex and expensive to setup independent refining facilities, it may be cost and environmentally beneficial in the long term. If it is financially feasible, a backup fossil fuel system may be desirable.

As stated in the refining section, certified fuel is often required for most biofuel burning equipment. It is important to verify that the fuel supplier is meeting the most recent fuel quality standards. The most recent standards can be obtained from the biofuel trade associations [7, 8]. These standards continue to be under development and receive frequent updates as the modern biofuel industry is not as mature as the fossil fuel industry. It is essential that fuel specifications are passed on to the boiler, engine, or turbine manufacturer to determine if the performance estimates are accurate as well as if the fuel will void the product warranty.

While getting biofuels to your site is a challenge, the U.S. Department of Energy's National Renewable Energy Lab (NREL) has assembled a map to assist biofuel users in determining where high concentrations of biofuels are likely to exist. Figure 4 below shows the approximate quantity of biofuel generated per year by location.

Fuel Delivery and Storage

Fuel storage is often a necessary part of biofuel systems, and there are a number of considerations to be



Biofuels and Sustainable Buildings. Figure 4
Biofuel potential by county for the USA [1]

investigated. First and foremost are fire code requirements, as biofuels, while often safer than fossil fuels, still pose a significant risk. The fire code is doubly important if fuel refining is done on-site as well. Local fire codes may not address biofuels and therefore fossil fuel requirements may be applied or a state fire code. Most biofuel trade associations will provide some assistance in the areas of fire safety.

The first step in storing fuel is getting the fuel from the delivery vehicle to the storage tank. For the biodiesel and ethanol, modified gasoline and diesel delivery vehicles are typically used, and are frequently available due to the large gasoline and diesel fuel infrastructure that exists. Again, local codes will designate safety features required to fill the storage tank. Independent biogas delivery is often done the same way as a standard natural gas line.

Wood pellets and chips vary in delivery methods. As such, the fuel transfer and storage system should be coordinated with the fuel supplier prior to design and construction. Some suppliers bring trucks that literally

suck pellets out of the truck via hose and shoot them into the storage container using compressed air. Other methods include small dump trucks that pour the chips or pellets into a trough where an auger will transfer the chips or pellets into a storage tank.

Biogas is rarely stored on-site as the process of getting it to site is somewhat complicated and dangerous. First, the biogas is pressurized and bottled off-site by the biogas producer. The biogas bottles are then transported by truck to the building site and stored until needed. The biogas bottles require the necessary gas regulators and explosion proof equipment to distribute the biogas to the boiler or engine that it will fuel. Biogas systems like this are typically reserved for experimental systems.

Sizing the storage tank is a function of first cost, delivery cost, and rate of fuel consumption. It will be an iterative process to balance these criteria as delivery costs and the rate of fuel consumption will vary over time as it is a function of load, which is difficult to project accurately, and projections are very difficult to

make accurately. The larger a storage tank, the higher the first cost both in construction and physical space required.

Once the storage size is known, the tank materials must be selected. While no exotic or expensive materials are required to store most biofuels, some common materials can cause issues.

Wood pellet and chip storage should be in a dry, weather-protected location. However, the spaces do not need to be conditioned by mechanical systems.

Brass valves and some elastomers (rubber) used in seals may be problematic over time for ethanol and biodiesel. The U.S. Department of Energy, National Renewable Energy Laboratory has published material compatibility documents for both ethanol and biodiesel [9, 10].

Biofuel Use

The use phase of biofuels is often of greatest interest to the building owner/operator. Biofuels can be used in boilers and hot water heaters, reciprocating engines, gas turbines, and fuel cells. Most equipment manufacturers have standardized their products to work well with existing technology, making retrofits and new designs relatively simple.

Boilers/Water Heaters Boilers and water heaters are available to be used with almost any biofuel. The most common commercial products are wood pellet and chip boilers for residential use. However, larger commercial boilers are becoming more common as fuel availability, delivering, and automatic feed systems have become more refined. The smaller residential units are typically available as packaged systems and are relatively easy to install. The larger commercial units are more complicated to install as storage and delivery systems need to be tailored for each site.

Fuel oil and natural gas boilers and water heaters may also be available in biodiesel and biogas variants on a case-by-case basis. The performance of these systems will vary based on the manufacturer, but in general manufacturers of boilers and water heaters have gone to great lengths to achieve equivalent or better performance than conventional boilers regardless of fuel type.

The only noticeable change will likely be in the quantity of fuel burned to achieve the same output. For example, the energy density of pure biodiesel is approximately 5% less than that of standard fuel oil. As such, approximately 5% more biodiesel would need to be burned to achieve the same heat output. That said, all fuels, fossil and bio, have energy density tolerances and vary in quality over time depending on a variety of factors based on the recent inputs into the refining process.

The operators need to be aware that running a boiler in a not so cold month with a lower quality fuel may consume more gallons than a colder month with high-quality fuel. That said, prices should reflect the average value of the fuel delivered over the course of a year. Therefore, the cost per unit energy may be high one month and low the next; so it will balance out. The alternative is testing each batch of fuel to determine its energy density, which would be very costly.

Some issues exist with biomass boilers during low load conditions. Strict temperature controls should be put in place to properly regulate the burning of biomass. Low burning temperatures may cause the emissions to change, and create significant carbon monoxide and particulate issues. This will be revisited in the emissions section, but some manufacturers have addressed this issue in their product designs.

Ash removal is also a concern for biomass boiler operators. Like any fire, a small quantity of ash remains that must be disposed of. In facilities with significant land available, the operators may consider dumping the ash on-site as the plants may benefit from the increased nutrients. Any use of ash on-site should be coordinated with a personnel qualified to understand how the local plants will be effected by mixing ash into the soil. Some plants and soil will benefit, while others may be harmed. Urban users of biomass will need to coordinate waste removal with the local refuse company to verify if ash can be land filled or otherwise disposed of in a safe manner.

Reciprocating Engines, Gas Turbines, and Fuel Cells (Prime Movers) The alternative to burning biofuels to create heat is to use the fuel in an engine, turbine, or fuel cell to generate electricity and heat. The function of these systems is essentially unaltered; however, the performance and maintenance may change noticeably.

As of July 2009, NREL estimated that 10.5 GW of electricity was being generated with biofuels with a total potential of 78 GW [1].

Similar to the biofuel boilers and water heaters, manufacturers of prime movers (engines, gas turbines, fuel cells, etc.) have been addressing the compatibility of their products for use with biofuels. As stated in the boiler/water heater section, the energy density of the fuels may vary and the prime movers are no less affected by this difference. Often fuel pumps and capacities are oversized in many systems to account for peak demand operation. Some of this spare capacity is used to feed more biofuel into the prime mover to maintain the desired power level. For example, a Diesel engine fueled with 100% biodiesel operating at 30 kW (40 Hp) will consume fuel as if it were operating at approximately 32 kW using Diesel fuel.

Table 1 shows a selection of prime movers with some general comparisons.

The exhaust and reject heat streams of the prime mover perform nearly identically to fossil-fueled prime movers [11]. Therefore, converting a cogeneration plant from fossil fuel to biofuel may not require the balance of plant to be altered to maintain functionality.

Changes in maintenance cycles are often the cause of the greatest failures of biofuels. For example, a building operator may have been maintaining backup natural gas engine generators for years. However, if an owner has replaced the natural gas fuel supply with

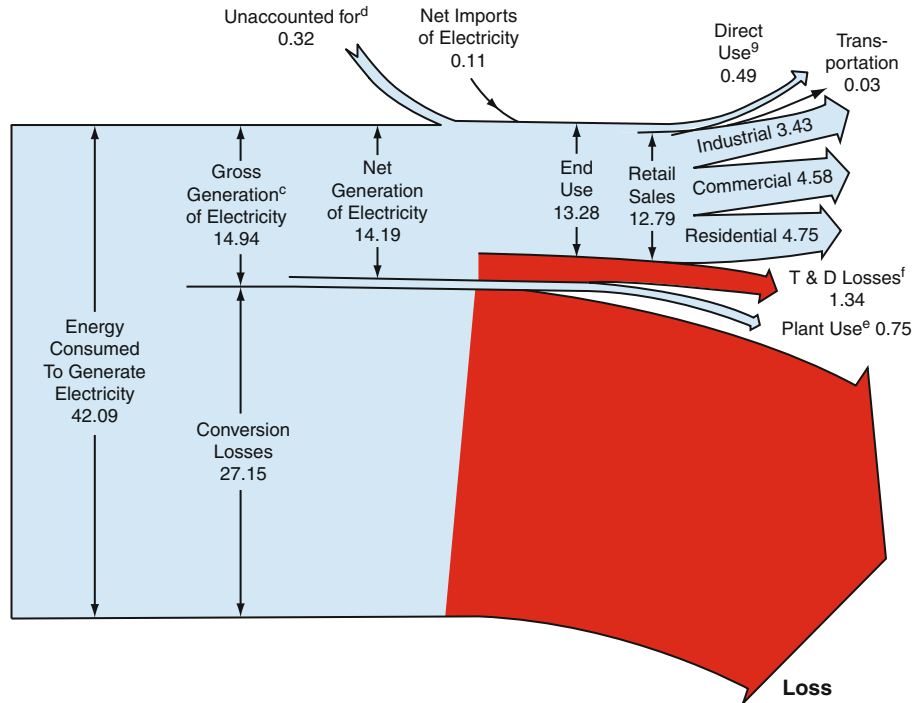
biogas, the previous maintenance cycles may be completely out of sync with the new reality. If the biogas is not the same quality as the natural gas, and is somewhat more corrosive, the engine seals could break down prematurely or the cylinders themselves could start to corrode. The operator must be vigilant about system performance and perform consistent maintenance checks. Additional equipment may be required to inspect the engine as compared to a conventional gas system. As there are relatively few long-term studies of biofueled systems, it is important for the building operator to coordinate and train with the prime mover manufacturers to avoid potential failures.

Cogeneration Prime movers are often paired with heat recovery systems to make combined heat and power (CHP) systems also known as cogeneration systems. The advantage of a cogeneration system versus grid power and standard boilers is that power plants waste approximately two-thirds of the fuel energy in the form of reject heat. Figure 5 shows the energy flow for the US power grid with approximately 68% of fuel energy being lost in conversion and transmission and distribution losses. With a cogeneration system, the majority of this energy can be recovered for useful purposes such as space heating and cooling.

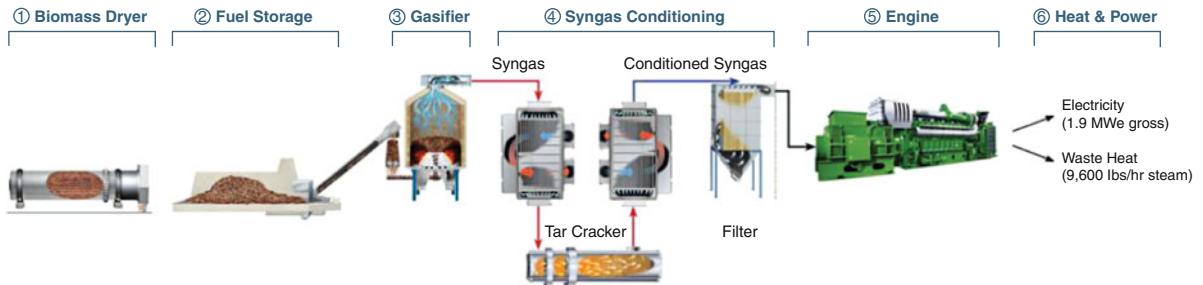
The example shown in Fig. 6 shows a complete biomass gasification and cogeneration plant.

Biofuels and Sustainable Buildings. Table 1 Prime mover comparison by fuel, efficiency, and heat

Prime mover	Fuels	Electrical efficiency	% recoverable heat	CHP efficiency	Heat to power ratio
Boiler + steam turbine	Natural gas, coal, waste fuels, biomass	10–15%	45–65% low-quality steam	65–80%	4.3
Gas turbine	Natural gas, biogas	15–25%	45–55% 600°F exhaust	60–80%	2.8
IC engine					
-Diesel	Diesel, biodiesel	30–40%	15–20% 190°F coolant, 15–20% 900°F exhaust	60–80%	1.6
-Spark	Gasoline, E85, natural gas, biogas	20–42%	15–30% 190°F coolant, 15–20% 900°F exhaust	50–80%	2.0
Fuel cell					
-SOFC	Natural gas	35–45%	25–35% 500°F exhaust	60–80%	0.8
-PEM	Hydrogen	35–45%	25–35% 300°F exhaust	60–80%	0.8



Biofuels and Sustainable Buildings. Figure 5
U.S. Electric grid energy flow [12]



Biofuels and Sustainable Buildings. Figure 6
Cogeneration and biomass gasification plant [5]

This biomass plant includes a substantial amount of conditioning equipment for the synthetic gas (syn gas) created by the gasifier to clean it prior to use in the engine. Alternative systems that use boilers rather than engines may use less conditioning equipment.

Emissions

Emissions are of great concern to many biofuel operators as many emissions are regulated by the U.S. Environmental Protection Agency as well as state

environmental agencies. Of particular concern are NO_x and particulates generated by combusting fuels. Unfortunately, characterization of emissions from biofuels is not a straightforward process. As stated, the quality and type of biofuels can vary and some equipment may not maintain optimal emissions in part load conditions. As such, emissions monitoring may be required for a period of time by local regulators to verify the installation meets local code. This is especially true in emissions non-attainment zones that provide additional focus on individual pollutants.

Biomass Emissions are of particular concern to regulatory bodies when the boilers are operating in part load conditions. As with any fuel, the temperature at which the fuel burns directly impacts the emissions characteristics. As the temperature decreases, carbon monoxide and particulates are formed. There are a number of ways to treat emissions, which include natural gas-fired afterburners to complete combustion and reduce particulate sizes.

Moisture content is also a large influencing factor in the emissions of biomass. Biomass moisture content below 50% is typically required by most boiler and water heat manufacturers [13, 14]. High moisture content will have the effect of boiling the water inside the fuel. As the water is turned to vapor, it will displace the oxygen in the combustion chamber and reduce the completeness of combustion leading to the creation of carbon monoxide. As a rule, the drier the fuel the better, but also the more expensive the fuel will be. Figure 7 shows a comparison of emissions for wood combustion.

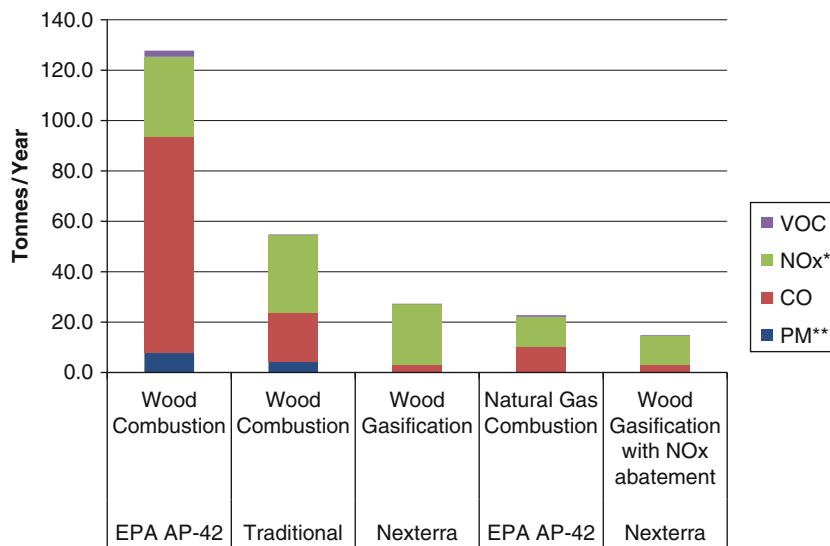
Biodiesel Biodiesel can come from many sources including soybean oil and coconut oil. While the thermodynamic performance of these two biodiesel sources may be similar, their emissions characteristics are quite different. As a rule of thumb, soy-based biodiesel,

which is the most common biodiesel source in North America, creates 5–10% more NO_x per kWh than diesel fuel. The emissions characteristics of the biodiesel are dependent on the molecular makeup of the original oil, especially polyunsaturated fat content. Soybean oil has a lot of polyunsaturated fat, as shown in Fig. 8, which indicates that the molecular structure has a lot of double bonds [15].

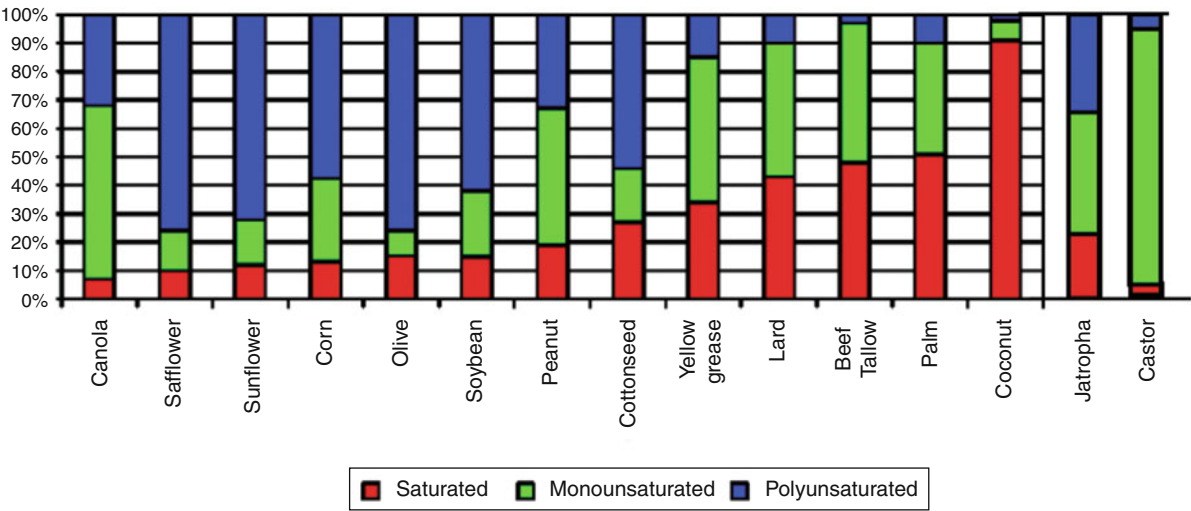
The consequence of double bonds is that the freezing point is low, which is good, but the cetane number is also low and somewhat unstable in an oxygen environment resulting in increased NO_x emissions [16–19]. Coconut oil on the other hand has very few polyunsaturated fats and a lot of saturated fats. Therefore, coconut oil-based biodiesel has a high freezing point, a high cetane number, is stable in oxygen environments, and has reduced NO_x emissions as shown in Figs. 9 and 10 [16–19].

As the emissions characteristics change per fuel type and content, and the status of pollutants changes per location; the design team must correlate local environmental regulations with available fuel supply to find the right match.

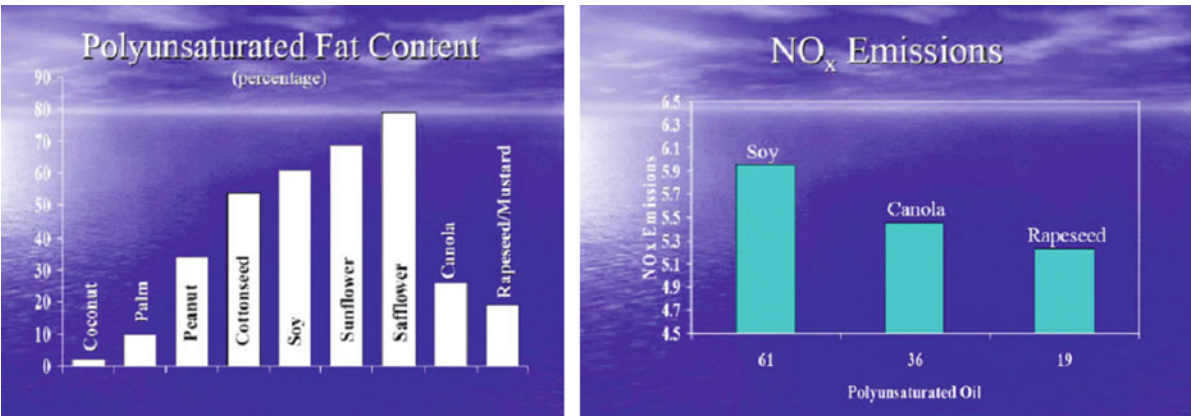
Carbon Neutrality of Biofuels Biofuels in and of themselves are carbon neutral because burning a certain mass of wood to generate heat will release



Biofuels and Sustainable Buildings. Figure 7
Comparison of wood combustion systems [5]



Biofuels and Sustainable Buildings. Figure 8
Average chemical makeup of oils [15]



Biofuels and Sustainable Buildings. Figure 9
Polyunsaturated fat content of oils versus NO_x emissions [16]

Fuel Property	Saturated 0 double bonds	Monounsaturated 1 double bond	Polyunsaturated multiple double bonds
Freezing Point	High (–)	Medium	Low (+)
Cetane Number	High (+)	Medium	Low (–)
Oxidative Stability	High (+)	Medium	Low (–)
NOx Emissions	Reduction(+)	Medium Increase	Large Increase (–)

Biofuels and Sustainable Buildings. Figure 10
Fuel properties versus chemical makeup [17–19]

a certain mass of carbon dioxide into the air, which will then be absorbed by another tree to grow approximately the same mass of wood. This cycle is what is typically considered when calculating carbon neutrality and set in comparison to fossil fuels emissions.

However, these calculations often do not include the carbon emissions that are generated during farming, harvesting, refining, and distributing biofuels or fossil fuels. Completing a detailed life cycle analysis to determine precisely how much CO₂ is generated from a fuel can be challenging.

In general, the savings shown in Fig. 11 can be used to estimate savings of cogeneration and biofueled cogeneration versus standard heat and power generation.

Common sense can go a long way in determining the carbon impact of the harvesting, refining, and distribution of a biofuel for a building or campus. If wood pellets are made from waste wood from a nearby lumber mill, then the building owner can be reasonably certain that the CO₂ generated by collecting the waste wood, processing it into pellets, and shipping it the site are relatively small as compared to the boiler emissions.

However, if the biofuel must travel a large distance by truck, in an attempt to offset natural gas delivered via pipeline, then the owner may want to attempt a life cycle analysis. There are a number of sources that

specify how much CO₂ is produced per mile traveled, or per unit energy consumed to assist in calculating a rough life cycle analysis [20–22].

Operating Costs

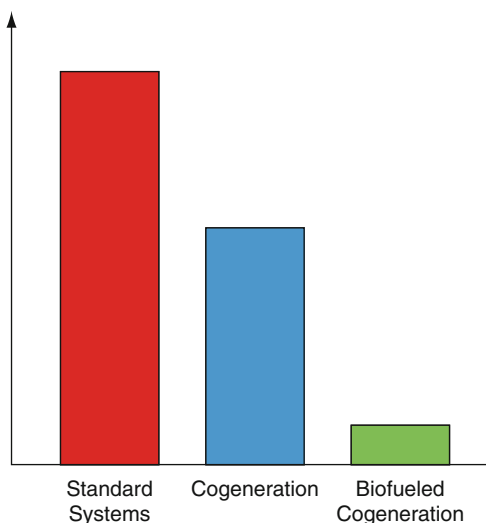
One of the largest pillars of sustainability is operational cost and operational performance. For owners and operators to be able to maintain effective operation of any system and their business, the following principles are good practices to avoid major cost fluctuations.

Buy Local First, pick the biofuel based on local availability. The distribution infrastructure for many biofuels is still weak, so most biofuels are shipped by truck. A closer supply chain is a great asset, and may give the owner some influence over regulation and pricing with the local government.

Quantify Supply Running out of the desired biofuel is a real concern in many parts of the USA, so it is important to identify multiple suppliers of the desired fuel. It is also important to understand the fuel supplier's supply chain and determine their vulnerabilities. Good things to look out for are large potential biomass sources such as lumber mills, nearby biofuel refineries, and landfills or wastewater treatment facilities. These fuel sources represent significant infrastructural investments and are unlikely to shut down rapidly.

Understand Competition The feedstock cost is the single largest influencing factor in the final cost of the refined biofuel. In 2008, the price of many food crops increased dramatically due to increased worldwide food demand and use of food crops for energy. Similarly, a demand for waste fryer oil changed the way restaurants and cafeterias view this waste stream. Several years ago restaurants had to pay to remove waste grease, then they were able to give it away to ambitious “do it yourself refiners,” and now there is a commodity value to waste grease in some markets where refiners are purchasing the waste grease from restaurants. Identifying potential competition for the biofuel feedstock may alleviate future cost spikes.

Fuel Flexibility Fuel flexibility is the other option to reduce long-term fuel costs. The best example of this



Biofuels and Sustainable Buildings. Figure 11
CO₂ generation of standard systems and cogeneration

concept is the flex fuel engines that run on E85. The E85 engine can run on any ratio of gasoline and ethanol below 85% ethanol. In other words, the fuel tank can be filled with E85 one day, and regular gasoline the next day as desired. Most gas turbines or engines that can run on biogas can also run on natural gas. The same is true for Diesel engines with respect to biodiesel and Diesel fuel. Some boilers can be co-fired natural gas and biomass, but this should be coordinated with the manufacturer.

Fuel flexibility is important in case there is a supply interruption, such as a reduced availability of biomass for the biogas digester, or a scheduled shutdown by lumber mill, or an equipment failure at the refinery. Suppliers may have contingencies in place to provide a supply during shutdowns. Also, building owners/operators may want to include a backup supply that could bridge the gap during outages. The size of the storage is a function of the load and how many days the supply needs to last.

Most fuels are regulated for quality by the American Society for Testing and Materials (ASTM) including ethanol and biodiesel [23–26]. Biogas must meet the local gas company's standards if it is to enter the natural gas network. Similarly, the biomass must meet the boiler manufacturer's standards in order to not void the warranty.

Future Directions

The technology to effectively employ biofuels into mainstream operation exists and has been effectively demonstrated throughout the USA and the world. Significant improvement needs to be made in the area of documentation and education of engineers, owners, operators, and code officials. Like any other industry, this will happen over time as owners request biofueled systems as an alternate to fossil-fueled systems. Owners and governments need to be willing to send their operators and code writers for training to assist in the adoption of these technologies. As owners increasingly demand biofueled systems, building designers, engineers, and the associated services will follow suit to meet demand.

The largest hurdle for the successful long-term operation of biofuels is understanding the minor differences between fossil fuel systems and biofuel

systems. Often building operators will fail to see the subtle difference between the systems that can cause unnecessary problems or failures in long-term operation, and cast doubt on the biofuel industry or a particular technology. As the body of knowledge and experience grows, installers and operators will learn to benefit from the advantages of biofuels and avoid the potential pitfalls to make biofuels as common a part of building operations as fossil fuels are today.

Outside of building operations, continued improvement in supply chain management to keep costs under control will be the largest deciding factor for the long-term success of biofuels. A great deal of research is being conducted to replace the use of food crops as a biofuel feedstock with nonfood alternatives such as wood chips, grass clippings, algae, and other biomass residue as well as increasing the efficiency of refining biofuels.

Biofuels will solve some of the pollution problems faced by the building industry today as well as help diversify the energy portfolio to enhance price stability and energy security. Biofuels along with cogeneration systems will become increasingly attractive as fossil fuels become costlier and environmentally riskier to extract over time. However, biofuels are a commercial commodity and as such will be subject to market forces and the laws of supply and demand. The same price fluctuations that effect transportation fuels today are already starting to affect the biofuel market as demand increases. Owners and operators will need to be aware of where their biofuel comes from as the impacts may be felt more acutely by a local population as opposed to fuels that come from the other side of the world.

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Biofuels: A Technical, Economic and Environmental Comparison

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Article Outline

Glossary
Definition of the Subject
Introduction
Characteristics of Technologies
System-Technological Assessment
Economic Assessment
Environmental Assessment
Conclusions
Future Directions
Bibliography

Glossary

BtL Biomass to liquid
CH₄ Methane
CO Carbon monoxide
Co Cobalt
CO₂ Carbon dioxide
DDGS Distiller-dried grained solubles
DE Diesel engine
DE Diesel equivalent
DME Dimethylether
EJ Exajoule
eq Equivalent
EU European Union
EUR Euro
FAME Fatty acid methyl ester
FC Fuel cell
FE Fuel equivalent

FFA Free Fatty Acids
FFV Flexible fuel vehicle
FT Fischer–Tropsch
GHG Green House Gas Emissions
GWP Global warming potential
H₂ Hydrogen
HVO Hydrogenated vegetable oil
Hyb Hybrid engine
IEA International Energy Agency
km Kilometer
LCA Life cycle assessment
LCI Life cycle inventory analysis
LCIA Life cycle impact assessment
MeOH Methanol
MJ Megajoule
mn Million
Mo Molybdenum
Ni Nickel
OBR Onboard reformer
OE Otto engine
OECD Organisation for economic co-operation and development
R&D&D Research & development & demonstration
SNG Synthetic natural gas
SRC Short rotation coppice
TCI Total capital investment
th Thermal
US United States
VO Vegetable oil
WTW Well-to-wheel
ZnO Zinc oxide

Definition of the Subject

Biofuels are liquid, gaseous, and solid fuels derived from biomass based on a broad variety of conversion processes. Despite this definition that encompasses all physical states, the term “biofuels” has been linked throughout the years with the transport sector and considers only liquid and gaseous fuels as an alternative solution to fossil fuels that are used in transport. This entry will follow this trend and will consider under the term “biofuels” fuel options of biomass origin that are used (or intended to be used) within the transport sector. While fossil-based electricity and heat could be replaced from electricity and heat produced from different renewable sources (e.g., sun,

wind), the only way, nowadays, to replace fossil fuels within the transport sector is biomass-based fuels; their importance is therefore undeniable, although their implementation is not free of concerns. The most important drivers for their implementation are the need for diversification of fuel sources, the fluctuations of fossil fuel prices and the associated need for security of fuel supply, and the need for mitigation of greenhouse gas emissions caused by the transport sector. Considering the variety of biomass conversion pathways, this entry provides a comprehensive analysis of current and most promising future biofuels options and highlights technical, economic, and environmental aspects along the entire production chain: from biomass production and transport, over biofuels production and distribution, to the final use of the biofuel (e.g., [1, 2]).

Introduction

Globally, many countries have been motivated to explore alternative energy sources due to increasing fossil fuel prices in average, energy supply security, and environmental consciousness (especially related to climate change). In developed and developing countries, fossil fuel price fluctuations and climate change are driven to the increasing interest in biofuels. Most developed countries are moving from voluntarily to obligatory legislations imposing market shares of biofuels in the transport sector [3]. With careful concepts and appropriate regulations, some biofuels might help to slow down global warming and to enhance energy security. Additionally, biofuels might provide countries opportunities to diversify agriculture production, to raise rural incomes, and to enhance access to commercial energy, especially for rural communities. However, media about the unintended side effects of bioethanol and biodiesel production has dominated the news about biofuels in the past. These headlines range from increasing world hunger and endangering forest reserves to increasing water pollution and wasting public funds [4].

Currently approx. 10% of the global primary energy demand (in 2007 approx. 516 EJ) is covered by biomass [5]. At present due to favorable policies and subsidy support in many countries, bioethanol based on sugar and starch crops (in 2009 approx. 58.4 million tons)

and biodiesel primarily based on vegetable oils (in 2009 approx. 14.4 million tons) are the most common biofuels representing approx. 2% of the total fuel consumption within the transport sector. Globally approx. 110 million tons of bioethanol and approx. 24 million tons of biodiesel are expected to be produced until 2020 which accounts for approx. 3.5% of the total global fuel consumption (Fig. 1).

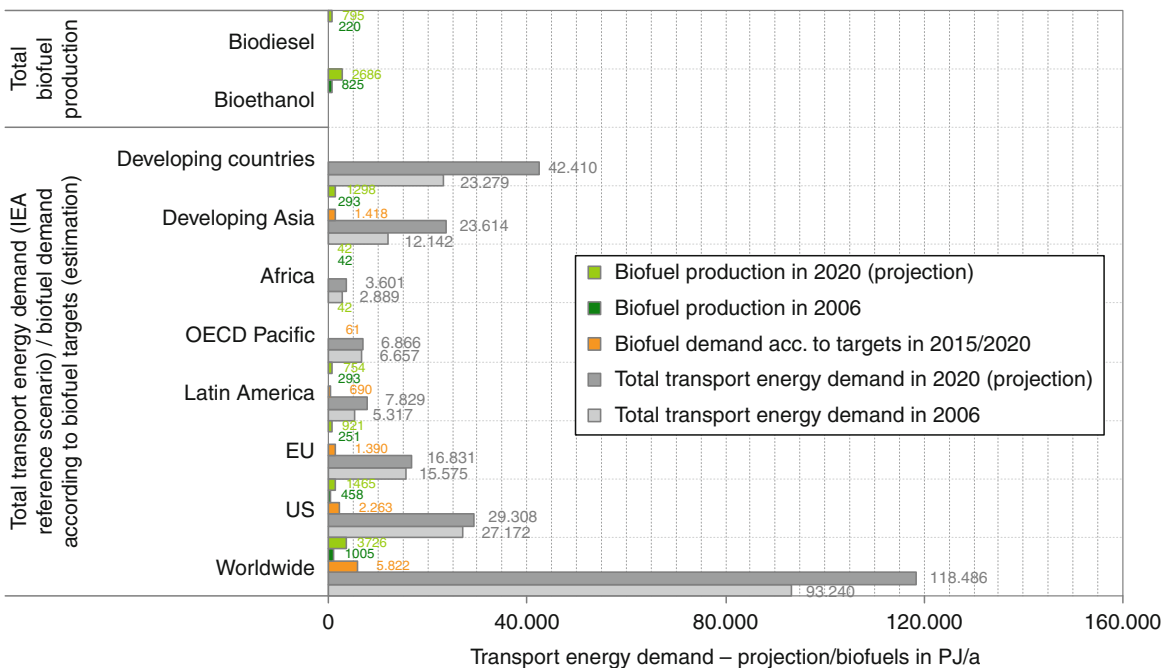
All over the world, an increasing number of countries define declarations on bioenergy use with special regard to biofuels. Motivations for that are different (e.g., decarbonization strategy in Europe, increased security of supply in America, Asia, and Africa). In Fig. 1, the required biofuels demand according to these biofuel targets is compared to the projected biofuel production and the total transport energy demand according to the IEA reference scenario. Even if assuming that the biofuels targets will be reached fully only approx. 25% of the global additional energy consumption within the transport sector (based on 2005) could be covered by the year 2020. It is expected that in this time frame, biofuels of future generation will only

play a minor role with regard to their current technology status and the expected business-as-usual development.

Against this background, this entry deals with the most important biofuel options for transportation purposes from a current point of view. Based on the characteristics of biomass as a multipurpose resource, technical profiles are shown for the different biofuel options. Furthermore, these technologies are considered concerning economic aspects (e.g., capital investment requirements, costs of production and use) as well as concerning environmental aspects (e.g., global warming effect).

Characteristics of Technologies

Advanced technologies are now under development to convert biomass into various forms of secondary energy including electricity, gaseous, and liquid biofuels. The purpose of biomass conversion is to provide fuels with clearly defined fuel characteristics that meet given fuel quality standards. In general, there are



Biofuels: A Technical, Economic and Environmental Comparison. Figure 1

Comparison of global transport energy demand, biofuel targets, and projected biofuel production (based on [5, 6])

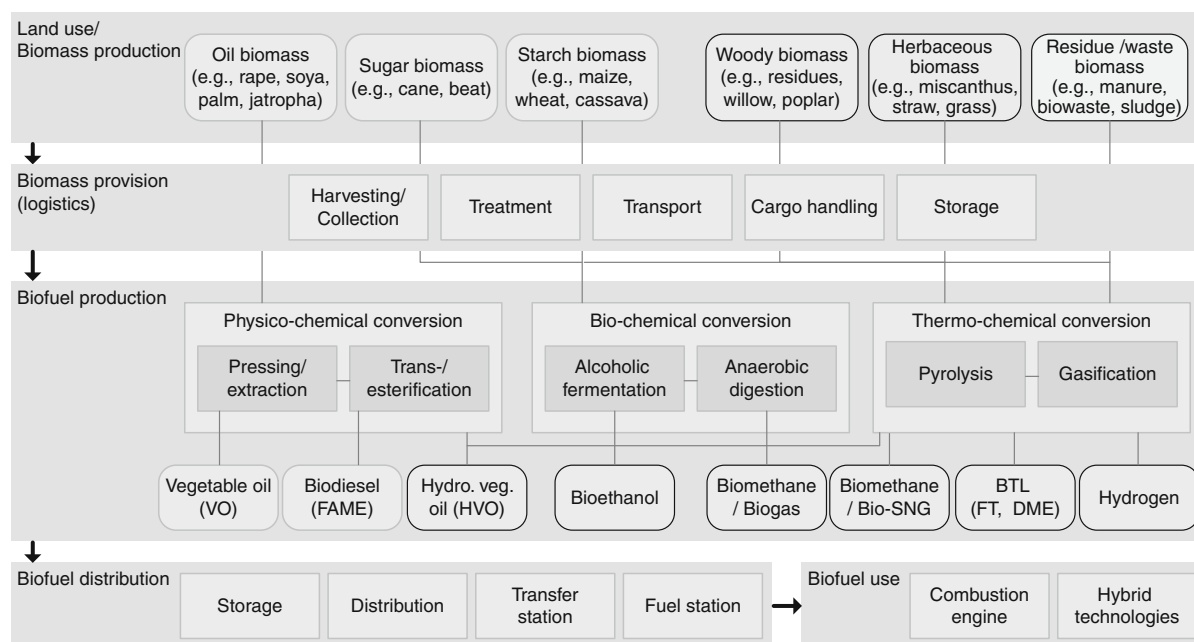
various options to produce alternative transportation fuels based on biomass. Depending on the conversion of biomass in principal, three main conversion pathways come into consideration: (1) the thermochemical pathway, (2) the physicochemical conversion pathway, and (3) the biochemical conversion pathway [7]. An overview is given in Fig. 2. For thermochemical and biochemical conversion, future lignocellulosic options might be promising. The use of lignocelluloses promises a larger non-food crop variety (e.g., woody and herbaceous residues and energy crops) with larger capacities and lower costs are expected at favorable environmental effects in future.

Current-generation biofuels are biofuels currently on the market in considerable amounts. The most important biofuels are bioethanol and ETBE and biodiesel using well-established processes for their production. For these types of fuels, only specific parts of the overall plant are used, such as the starch in corn kernels or grains, the sugar in canes or beet, or the oil in oilseeds. Residues from the production of these crops (e.g., straw) are currently used within the agricultural cycles (e.g., as fertilizer, for animal farming). Moreover, by-products accumulate during biofuel production

and can be applied in the fodder and the chemical industry (e.g., press cake, glycerine, fertilizer when producing biodiesel, and vinasse or DDGS when producing bioethanol).

- Bioethanol is produced by fermenting sugars from starch and sugar biomass (e.g., cereal crops such as corn or wheat and sugarcane or beets). It is applied in pure form in specially adapted vehicles or blended with gasoline, provided that fuel specifications are met. Ethyl-tertiary-butyl-ether (ETBE) is synthesized from bioethanol and isobutylene. It is used as additive to gasoline.
- Biodiesel or fatty acid methyl ester (FAME) made from vegetable oils from the reaction with methanol in a catalyzed transesterification process. It is used in pure form in specially adapted vehicles or blended with diesel.

Different from that future biofuels can basically be produced (1) from an expanded range of feedstock as well as (2) from the whole plant (i.e., much more biomass per hectare land), including biomass waste streams that are rich in lignin and cellulose, such as straw, grass, or wood. It is expected that low-cost



Biofuels: A Technical, Economic and Environmental Comparison. Figure 2

Simplified overview of biofuel pathways (future-generation feedstocks and biofuels marked in green)

residue and waste sources will be the primary feedstock for the next 10–15 years, followed by cellulosic perennial energy crops (e.g., willow, poplar, eucalyptus) with the potential to expand substantially after 2020 [8]. For the provision of these biomass sources, adapted logistic concepts (e.g., with regard to storage, transport, biomass handling) are required since logistic chain complexity increases with increasing biofuel plant size. In order to breakdown this biomass to produce biofuels with better fuel properties than, for example, vegetable oils and biodiesel, two main conversion pathways come into consideration:

- Firstly via biochemical processes that, for example, use special enzymes breaking down the lignocelluloses and releasing the sugars, which can then be fermented into bioethanol. Moreover, biogas that is produced from anaerobic treatment of biogas substrates and is then upgraded to biomethane, which can be fed into the natural grid and, for example, used in natural gas vehicles.
- Secondly via thermochemical processes based on gasification, where high temperatures are used to turn biomass into a raw gas that is treated and conditioned into a synthesis gas, consisting mainly of carbon monoxide and hydrogen. This gas can further be processed into different types of liquid and gaseous fuels via different types of fuel syntheses. Fuels from this route are then called “synthetic biofuels.” Most promising liquid synfuel (also BtL, biomass-to-liquids) is, for example, Fischer–Tropsch fuel due to its favorable fuel properties. Gaseous synfuels are, for example, dimethylether (DME) and bio-SNG, which is also a form of biomethane and can be similarly used as a substitute for natural gas-like biomethane from biogas. Furthermore, available vegetable oils or animal fats can be treated by hydrogenation processes into so-called HVO, a biodiesel with comparably more favorable properties than conventional biodiesel.

Typically, future-generation biofuels production plants and the surrounding infrastructure are more complex than conventional biofuel options and thus more capital intensive (i.e., high capital risk). The technical measures shown with the future-generation concepts are possible in principle but have to be

confirmed within future demonstration plants. Regardless of large differences of the different concepts under discussion, it also has to be pointed out that none of the concepts can be called “proven technology” that can be bought off the shelf as a turnkey plant. Some of the concepts show a promising maturity justifying the development of a first industrial demonstration project together with (industrial) monitoring. Except few demonstration plants under operation (e.g., for HVO, biomethane based on biogas and some bioethanol based on lignocelluloses, mostly integrated into existing conventional bioethanol plant), for all future-generation biofuels scale-up strategies are required. This includes the integration of the different process steps along the complete chain (biomass to transportation fuel) in order to demonstrate the effective process performances and reliability. Thereby the focus (also from an economic viewpoint) must be to achieve industrial reliability and technical performance (energy integration to achieve high efficiency/yields). According to this, it is attractive to build up HVO and BtL plants very close to crude oil refineries in order to use their infrastructure (e.g., with regard to hydrogen supply required for fuel upgrading). Moreover, existing biofuel concepts (e.g., for bioethanol) show the potentials to be a part of the so-called bottom-up approach for biorefinery plants that can function as multiproduct provider (e.g., biofuels, bulk chemicals, fertilizer, energy).

Therefore, enormous R&D&D efforts are required, including the demonstration of the overall chain under industrial conditions (including wastewater management, health and safety aspects, etc.) to prove (1) efficiency, (2) reliability, and (3) operability, also taking into account lessons learned from the implementation of conventional biofuels [6, 9, 10].

Biodiesel

Diesel based on biomass (i.e., biodiesel) can be produced by means of various production routes [1]:

- Via the physicochemical conversion by means of transesterification of vegetable and animal oils and fats; this is the most established pathway for biodiesel worldwide
- Via the thermo-chemical conversion by means of hydrogenation of bio-oils (e.g., palm oil) within

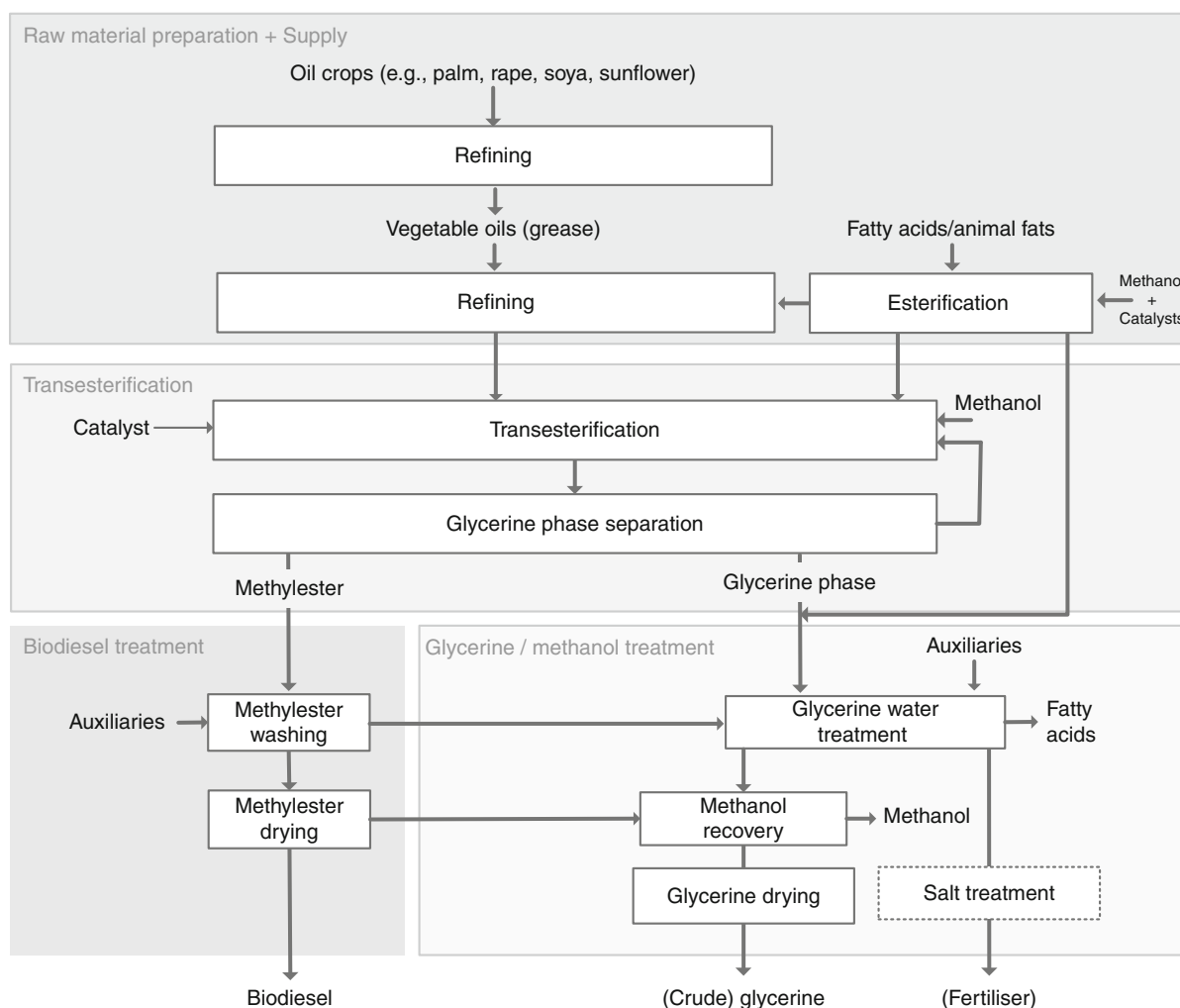
refinery processes that are established for the production of conventional diesel fuel from crude oil; this is still a niche option

Conventional Biodiesel Biodiesel production based on physicochemical conversion typically consists of the production of vegetable oil and fats via mechanical and/or solvent extraction (often within a combined process), followed by (trans)-esterification and the final treatment to biodiesel (Fig. 3). Today, resources for biodiesel are mainly vegetable oils produced from oil-containing crops (e.g., rape seeds, palm fruits, soy

seeds, sunflower seeds). The oil crops (i.e., seeds and fruits) are characterized by a different specific total oil content, which are in the range of, for example, 17% for soy beans (with soy oil as by-product of soy meal production) to about 38% for rape seeds.

Chemically, transesterification (also called alcoholysis) means taking a triglyceride molecule (i.e., vegetable oil) removing the glycerine by substituting with an alcohol (e.g., methanol) and thus creating a so-called fatty acid methyl ester (FAME).

There are three basic steps in the biodiesel production from oils/fats: (trans)-esterification, ester processing, and glycerine purification. Therefore, oil is



Biofuels: A Technical, Economic and Environmental Comparison. Figure 3

Principle of conventional biodiesel production

charged to the reactor and mixed with the alcohol (e.g., methanol) and the catalyst (typically hydroxides like NaOH or KOH or their methylates). A successful transesterification reaction produces two liquid phases: (1) methylester and (2) glycerine. Once separated from the glycerine, the ester is washed to remove any soap formed during the reaction as well as the residual free glycerol and alcohol. The ester is then dried to remove all water. In some cases, the esters are distilled under vacuum to achieve even higher purity in the fuel by removing sulfur and/or phosphorus. The washing step can be greatly affected by the free fatty acids (FFA) level of the feedstock, since all the FFA form soaps in the reaction.

To further refine the glycerine, it is neutralized with an acid to form salts and sent to storage as crude glycerine. Depending on the applied catalyst, surplus catalyst KOH and soaps can be split by producing, for example, potassium sulfate that can be applied as fertilizer. After the aqueous glycerine phase has been neutralized, the glycerine is processed further by evaporation. The glycerine is then typically 60–88 wt.% pure. The glycerine can again be further refined by drying it in a vacuum distillation unit and then cleaned in a continuous adsorption unit to receive technical or pharmaceutical-grade glycerine (up to 99.5 wt.%).

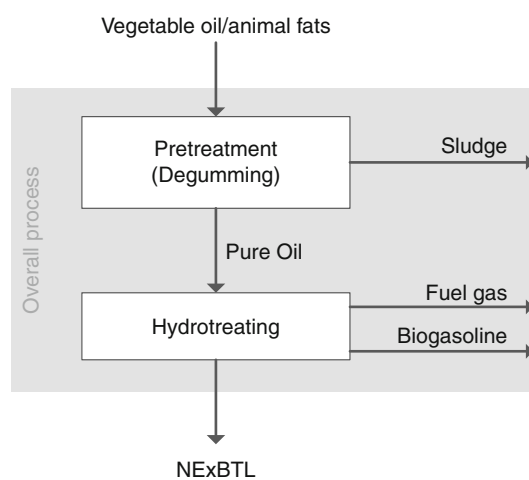
The excess methanol can be removed at different stages of the reaction – before or after the phase separation. In both cases, the methanol is recovered and reused using conventional equipment. Care must be taken to ensure that no water accumulates in the recovered methanol stream.

Depending on application schemes, biodiesel plants are designed in different capacity scales (e.g., from approx. 0.5 kt/a to several 100 kt/a) and performance types (e.g., batch and/or continuous biodiesel processes with or without oil mills as annex plants). The kind and quality of feedstock is the decisive factor for the technical design of a plant and the corresponding material and energy flows [1].

Advanced Biodiesel In order to produce a biodiesel with more favorable properties than biodiesel based on the (trans)-esterification of vegetable or animal oils and fats (i.e., conventional biodiesel production), conventional refinery processes can be also applied to convert the same feedstock into an advanced biodiesel. Properties that are similar to petroleum diesel can be

achieved by blending vegetable oils with mineral oil previous to their upgrading to diesel in mineral refineries by using the existing refinery infrastructure including energy, blending facilities, logistics, and laboratories. One option, which is currently implemented at commercial level is the so-called NExBTL process [11]. The principle of this catalytic hydrotreating process is shown in Fig. 4. It is briefly explained below.

For the pretreatment of the feedstock (e.g., vegetable oils as crude oil, animal fats), conventional degumming technology known from vegetable oil processing or conventional biodiesel production is used to remove undesired impurities [11]. Firstly, the feedstock is filtered before reacting with hydrogen (demand approx. $0.09 \text{ GJ}_{\text{H}_2}/\text{GJ}_{\text{biodiesel}}$ [12]) and passing through the catalyst beds at elevated temperatures and low space velocities. The hydrotreating process typically takes place in fixed-bed reactors at temperatures of approx. 350–450°C and at a partial hydrogen pressure of 48–152 bar. For that, standard catalysts are applied (such as CoMo and NiMo) [13]. During hydrotreating, oxygen is removed by adding hydrogen. Vegetable oil or animal fats (i.e., triglycerides) are converted into three separate branched chain paraffins. Oxygen in the triglyceride is removed as water and carbon dioxide. Side products of the process are fuel gas, which can be used for energy and a small amount of biogasoline. The main product NExBTL has similar



Biofuels: A Technical, Economic and Environmental Comparison. Figure 4

Principle advanced biodiesel production

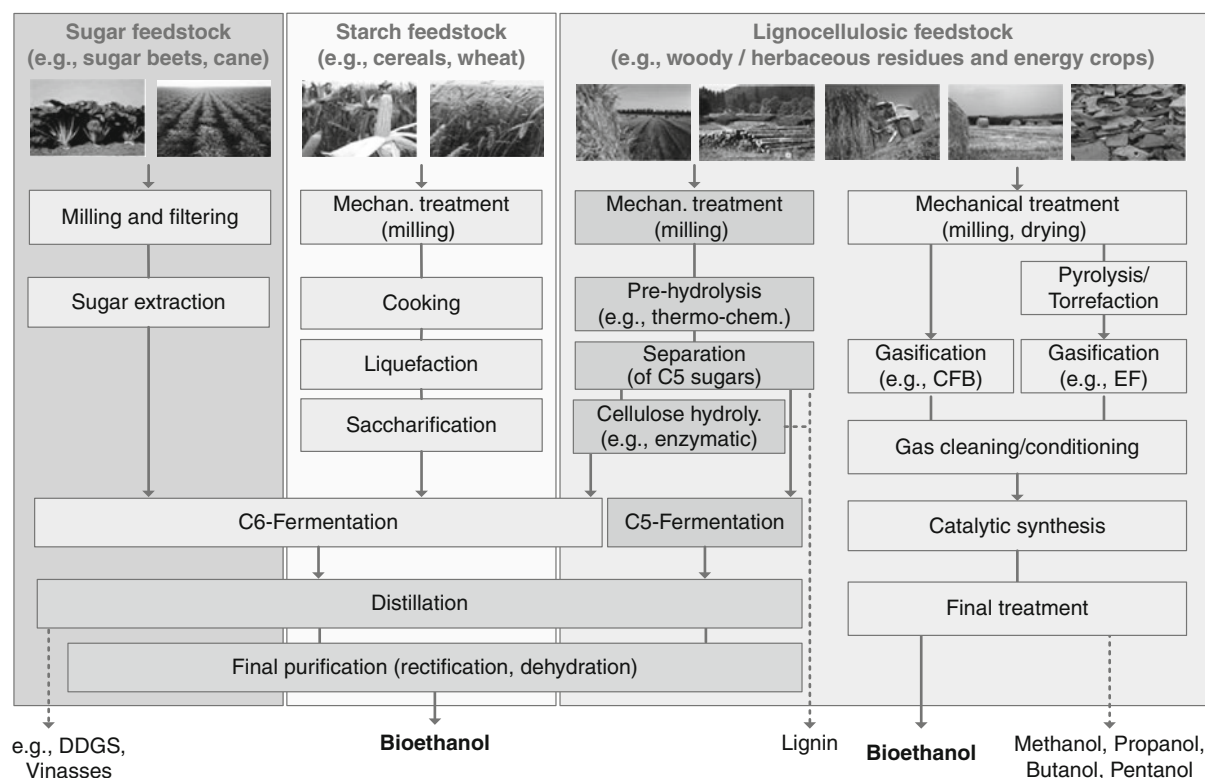
chemistry and properties to the synthetic BtL fuels (e.g., Fischer–Tropsch diesel). The mass specific biomass conversion rate is – depending on the feedstock – approx. $1.23 \, t_{\text{feedstock}}/t_{\text{biodiesel}}$ [11, 12].

Bioethanol

Bioethanol production is based on biochemical conversion processes (i.e., fermentation by microorganisms), which is also considered in the following (Fig. 5). Currently, worldwide conventional bioethanol is produced by using sugar crops (e.g., sugarcane in Brazil, sugar beet in the Europe) and cereals (e.g., corn in the US, wheat in Europe, cassava in Asia). The use of lignocelluloses offers several benefits regarding crop variety, feedstock costs and environmental impacts in the future. Technologies for conversion of lignocellulosic biomass to bioethanol are basically available. However, currently no commercial lignocellulosic bioethanol plant is being operated. The development of cellulosic

ethanol concentrates on three main regions: the US, China, and Europe. Often, second-generation plants (biochemical) are planned as annex facilities to conventional plants. In addition to biochemically fermented ethanol, bioethanol can be produced as synthetic fuel by thermochemical conversion (Fig. 5).

Conventional Bioethanol When using cereals, the first step within the conversion plant is a milling station. Here, the flour is mixed with water and recycled thin stillage to form a mash. By adding enzymes and a thermal treatment at temperatures between 60°C and 90°C, the starch in the mash is broken down to glucose. The sugar solution, originating from the saccharification is cooled down and is transferred to the fermentation vessel. The alcoholic fermentation is realized at 35°C, which is the optimum temperature for the metabolism of the fermenting yeast. Within the fermentation step, glucose is metabolized by yeast to form ethanol, CO₂, and biomass. The CO₂ resulting



Biofuels: A Technical, Economic and Environmental Comparison. Figure 5
Principles of bioethanol production

from the fermentation process is discarded to the environment or can be used to carbonate soft drinks.

After fermentation, raw bioethanol needs to be treated by distillation and final purification (dehydration). In the process of distillation, the alcohol contained in the mash (concentration of up to 5 wt.% [14]) is separated based on a multistage distillation/rectification using steam. Beside water, several other substances are removed from the ethanol. Furthermore, the coproduct mash is gained as distillation residue. The main desired product of the distillation process is azeotrope ethanol with a maximum purity of 97 vol.%. The subsequent process of dehydration is used for further concentration of ethanol (to achieve an alcohol concentration of at least 99.8 vol.%). For that the method of the molecular sieves has detached the older membrane and entrainer distillation. The use of the molecular sieves also allows the dehydration of ethanol with a purity of down to 85 vol.%. Thereby it is possible to save energy in the process of thermal rectification [15–17].

Apart from concentration of the ethanol, the bottoms of the distillation column (stillage) have to be treated. The stillage is virtually free of ethanol, but contains soluble and insoluble organic and even some inorganic material. The first treatment step consists of a mechanical separation with a decanter, which yields the thin stillage and a decanter cake [18]. Half of the thin stillage can be recycled to the initial mashing process, whereas the rest is fed to a series of two evaporators, in order to further concentrate the soluble substances to syrup. Finally, syrup and decanter cake are blended and dried to reduce the water content. The product of this drying step is marketed as DDGS protein fodder (digesters dried grains with solubles).

Lignocellulosic Bioethanol For the following process stages, the lignocellulosic feedstock is pretreated and grinded to a small particle size of approx. 1–3 mm. Depending on the kind of hydrolysis used in the following procedure, a drying of the treated material to a humidity of less than 10 wt.% may be necessary [15].

To make the sugars available for the fermentation step, hydrolysis (i.e., saccharification) is carried out. The first step of hydrolysis contains the release of fermentable monosaccharides C_5 (i.e., xylose, arabinose) and C_6 (i.e., hexose, glucose) from cellulose and hemicellulose. The second step of hydrolysis is typically based on an

enzymatic decomposition of the cellulose molecules. Alternatively, a single step process using concentrated hydrochloric and sulfuric acid could be used for cellulose extraction. Moreover, enzymatic procedures are still in the progress of development [14, 15].

In the next step, the sugars gained from hydrolysis are used as feed for the following process of fermentation. The remaining lignin could be used as a fuel for the production of process energy. Depending on the plant used, the process of fermentation takes between 2 and 5 days. Afterwards, the used mash contains 10–15 vol.% of ethanol. For process control, the used auxiliary materials are important (e.g., acids for the pH-value and ammonia for nutrient supply of yeast). These requirements in connection with an appropriate temperature are the basis of the yeast enzyme production and therewith of the glucose conversion to ethanol and carbon dioxide. For the fermentation of lignocellulose, the commonly used yeast is suitable only to a limited extent. From the contained sugar spectrum, only glucose, as a monomer component of the cellulose molecule, can be fermented to bioethanol. Based on biotechnological methods, new approaches for the fermentation of the whole sugar spectrum produced from lignocellulosic biomass have been developed over the last years [7, 14].

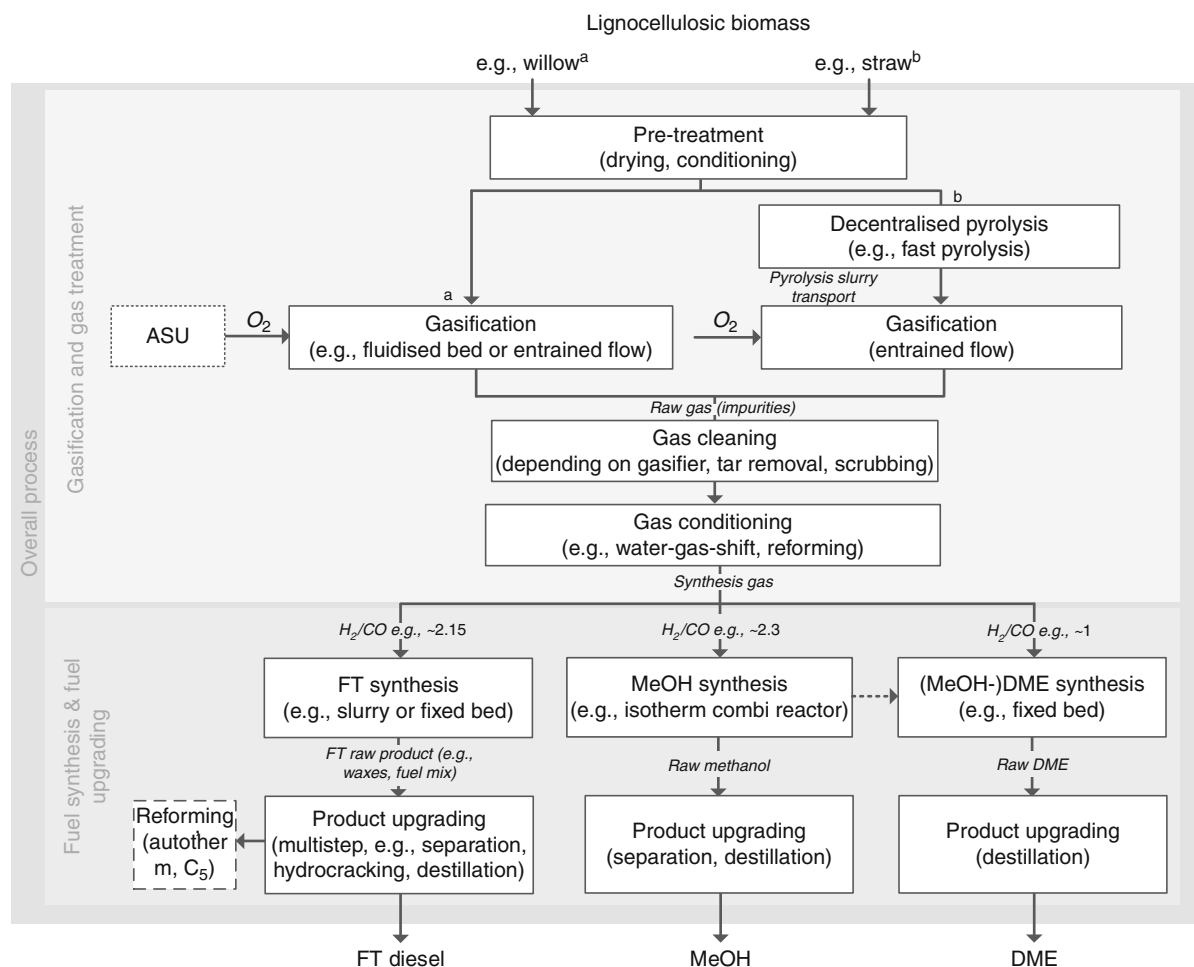
The additional steps for ethanol concentration are basically the same like for conventional bioethanol.

Synthetic Biofuels

The production of synthetic fuels (i.e., “designer fuels” with clearly defined properties) is characterized by three main steps to be performed after appropriate biomass pretreatment:

1. Gasification of lignocellulosic biomass to a raw gas
2. Cleaning and conditioning of raw gas to synthesis gas
3. Catalytic synthesis of this gas to synthetic biofuels (e.g., Fischer–Tropsch fuel, methanol (MeOH), dimethylether (DME), and synthetic natural gas (SNG))
4. Final product treatment

In the following, Fischer–Tropsch fuel (FT), biomethanol (MeOH), and dimethylether (DME) are briefly introduced. The principle is shown in Fig. 6.



Biofuels: A Technical, Economic and Environmental Comparison. Figure 6

Principle thermochemical synthetic biofuel production

Despite of a long history of the development of a broad variety of system elements as well as system layouts for the provision of liquid and/or gaseous fuels via biomass gasification, no market breakthrough has been realized so far. One reason is, for example, difficulties in combining different system elements to an overall turnkey plant. Additionally, some system elements are still under development. For an efficient production of synthetic biofuels with regard to “economy of scale” within the conversion plant as well as the minimization of the biomass transportation costs, conversion concepts of a medium to large scale are required. Such a medium to large scale is necessary to provide sufficient amount of raw gas for gas cleaning/

conditioning and fuel synthesis as well as to produce this gas via gasification at economically justifiable costs.

Regarding biomass pretreatment for gasification, mechanical-thermal biomass treatment (e.g., chipping and drying of solid biofuels) is mature. Processes to produce intermediate products that can be more easily transported and handled for gasification (i.e., pyrolysis and torrefaction) are still in a pilot/demo stage. Despite the scale of a gasifier, no gasification system is a priori appropriate for biomass. Among other criteria, chemical characteristics and physical and mechanical properties of the utilized biomass are of importance. However, all reactors for biomass gasification (e.g., fluidized bed reactors, entrained flow reactor) are still

in an R&D stage up to now. Furthermore, previous developments on gasification were mostly not focused on synthesis gas production but rather on the provision of a product gas intended to be used for heat and power generation.

Depending on fuel synthesis, specific qualities of synthesis gas at constant compositions and large amounts have to be provided (e.g., for the production of 100–1,000 m³_{STP}/h of FT). Quality criteria are, for example, a certain degree of gas purity and a specific H₂/CO ratio. Because so far no gasification system meets these requirements, appropriate gas cleaning and conditioning system have to be applied. During gasification, besides the main components (CH₄, H₂, CO and CO₂) also impurities are generated such as tars, coarse and fine particles, sulfur compounds, alkalis, halogen and nitrogen compounds, as well as heavy metals. Their quantities vary depending on the gasification process as well as the type of biomass. For raw gas cleaning, either low temperature wet gas cleaning or, alternatively, hot gas cleaning can be applied. The effectiveness of wet gas cleaning (e.g., cyclone and filter, scrubbing based on chemical or physical absorption) has been well proven for large-scale coal gasification systems. Contrary to that, not all elements of hot gas cleaning (e.g., tar cracking, granular beds and filters, physical adsorption or chemical absorption, ZnO-bed, physical absorption) are of mature technology yet. Nevertheless, hot gas cleaning offers benefits for the overall energy balance and with regard to the avoidance of contaminated sewage. For gas conditioning, available system components can be applied: hydrocarbons in the product gas can be converted by means of an additional steam or autothermal reforming step resulting in a higher H₂/CO ratio. To achieve the required quality for fuel synthesis, the water–gas CO conversion is conducted as final step of synthesis gas production [19].

The production of synthesis biofuels primarily differ regarding a catalytic exothermic synthesis and product upgrading:

- *Fischer–Tropsch (FT) fuels.* FT synthesis is a polymerization process at low temperature (200–240°C) whereby synthesis gas is liquefied into hydrocarbon chains of different length. This synthesis is catalyzed either by iron- or cobalt-based

catalysts. This conversion can be operated in a “full-conversion” or a “once-through” operation mode by using either tubular fixed bed or slurry bubble column reactor at an operating pressure range from 20 to 40 bars. The FT raw products consist of a wide spectrum of light hydrocarbons (C₁–C₄), naphtha (C₅–C₁₀), the main product FT diesel (C₁₁–C₂₀), and waxes (C₂₁₊) that need to be separated afterwards. Naphtha is a gasoline fraction of minor value and is used as a resource for the petrochemical industry. It can be upgraded to motor applicable gasoline by isomerization. Wax upgrading is done by hydrocracking. Within this catalytic oil refinery process, long-chained hydrocarbons are split into the desired diesel and middle distillates in the presence of hydrogen [20, 21].

- *Methanol.* The operating pressure of methanol synthesis ranges from 45 to 100 bar and the temperature from 220°C to 280°C. Catalysts needed to steer the conversion process are based on copper, zinc, and aluminum oxide. Like within the FT synthesis, in the methanol synthesis two reactor types are commonly used: (1) fixed-bed reactors (e.g., ICI-quench reactor, isothermal reactor, Linde-isothermal reactor, multiple-bed reactor) or (2) slurry reactors (e.g., suspension/slurry reactor). Within the synthesis, several by-products (e.g., DME, alkalis, ethanol, propanol, butanol) are generated in addition to the methanol fraction, which appear gaseous together with unconverted syngas fractions. For separating higher hydrocarbons from the product gas stream, an oil separator is used. Afterwards the raw methanol is separated by condensing, stored and upgraded in a distillation column [22–24].
- *Dimethylether.* DME can be produced via direct synthesis or via indirect synthesis over the intermediate product methanol. For large-scale application, the fully integration of the two process steps, methanol and DME synthesis (i.e., direct synthesis), is very advantageous and the best choice for DME production in terms of efficiency; but this option is still within the R&D stage. Classically two methanol molecules react to produce DME and water, which is removed. The reaction takes place at temperatures of about 250–300°C. Commonly fixed-bed reactors without any special internal heat

exchangers are used. Stoichiometric efficiencies of about 86–88% referring to the raw methanol can be reached. Besides water and undissolved gases, the generated raw DME contains little amounts of ether compounds and alcohols. The gases can easily be removed by reducing the pressure. Subsequently follows the final product cleaning by distillation [20].

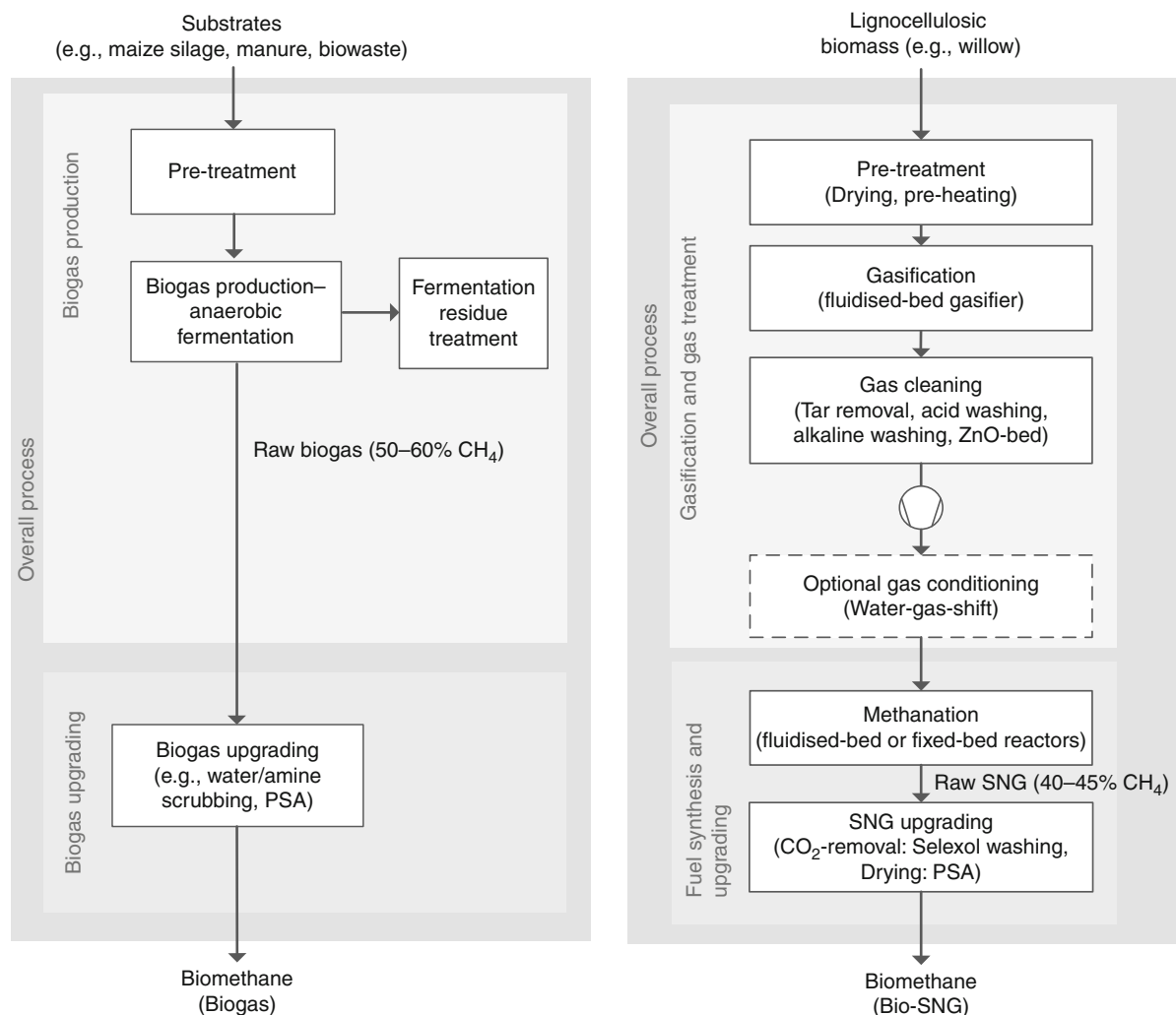
Biomethane (via Biogas and Bio-SNG)

The gaseous fuel biomethane can favorably be applied as a substitute for natural gas. This gas is produced

either through the biochemical conversion of biomass with a subsequent gas upgrading or through the thermochemical conversion of solid biomass via gasification with subsequent gas cleaning, methanation, and product gas upgrading.

In the following (Fig. 7), these two processes are briefly described.

Biogas Biogas production is based on anaerobic fermentation, which requires a substrate pretreatment. On their way into the fermenter, the substrates undergo the following steps: (1) the delivery to the plant, (2) the



Biofuels: A Technical, Economic and Environmental Comparison. Figure 7

Principle of biochemical (left) and thermochemical (right) biomethane production

storage, (3) the upgrading (e.g., homogenization), and (4) the transportation from the storage to the fermenter [25, 26].

For the biogas production by anaerobic fermentation, a broad variety of different kinds of biomass can be used (e.g., liquid and pasty substrates such as manure, biowaste, maize silage, and wastewater). During this biochemical degradation process, organic material is decomposed in an oxygen-free atmosphere by several types of bacteria that produce a gas containing approximately 50–66% methane (CH_4) and 33–50% carbon dioxide (CO_2) plus some impurities (e.g., sulfur compounds like H_2S) of minor importance and water vapor. Digestion is a complex metabolism chain, whereby each step is characterized by the attendance of special bacteria.

In order to feed biogas into the gas grid, the raw biogas has to undergo cleaning and upgrading process steps that include biogas purification from trace components (primarily H_2O , H_2S , and NH_3). Moreover, the heating value, Wobbe index, and other parameters, which highly depend on the CH_4 content, need to be adjusted to pipeline specifications by removing CO_2 . Some technologies enable the removal of H_2S and CO_2 in parallel. However, the relevance, feasibility, and sequence of the different cleaning and upgrading processes depend on the specific gas composition and pipeline specifications. Upgrading technologies for biogas result mainly from technological applications from the natural gas sector where partly comparable upgrading tasks have to be solved, but at a by far larger scale. Main technologies, where already experiences in practice exist, are, for example, water scrubbing, pressure swing adsorption, and chemical absorption (e.g., amine washing). Generally, it has to be stated that all processes available on the market pledge to reach a biomethane quality of more than 96% methane content and a methane loss with less than 3% [27].

Bio-SNG The SNG production is characterized by the possibility that relatively small conversion units with capacities in a range of 10 up to several 100 MW_{th} biomass input can be used. Thus, the conversion of locally available lignocellulosic biomass is possible to minimize the feedstock provision costs. The production of synthetic biofuel, electricity, and heat (so-called tri-generation) allows high overall

efficiencies (e.g., high GHG mitigation potential) within the entire production process. Compared to the production of BtL-fuels (like Fischer–Tropsch fuels) the SNG production system is characterized by lower technical and financial risks due to a technology that is less complex (e.g., synthesis and fuel treatment) and basically smaller units can be used [28].

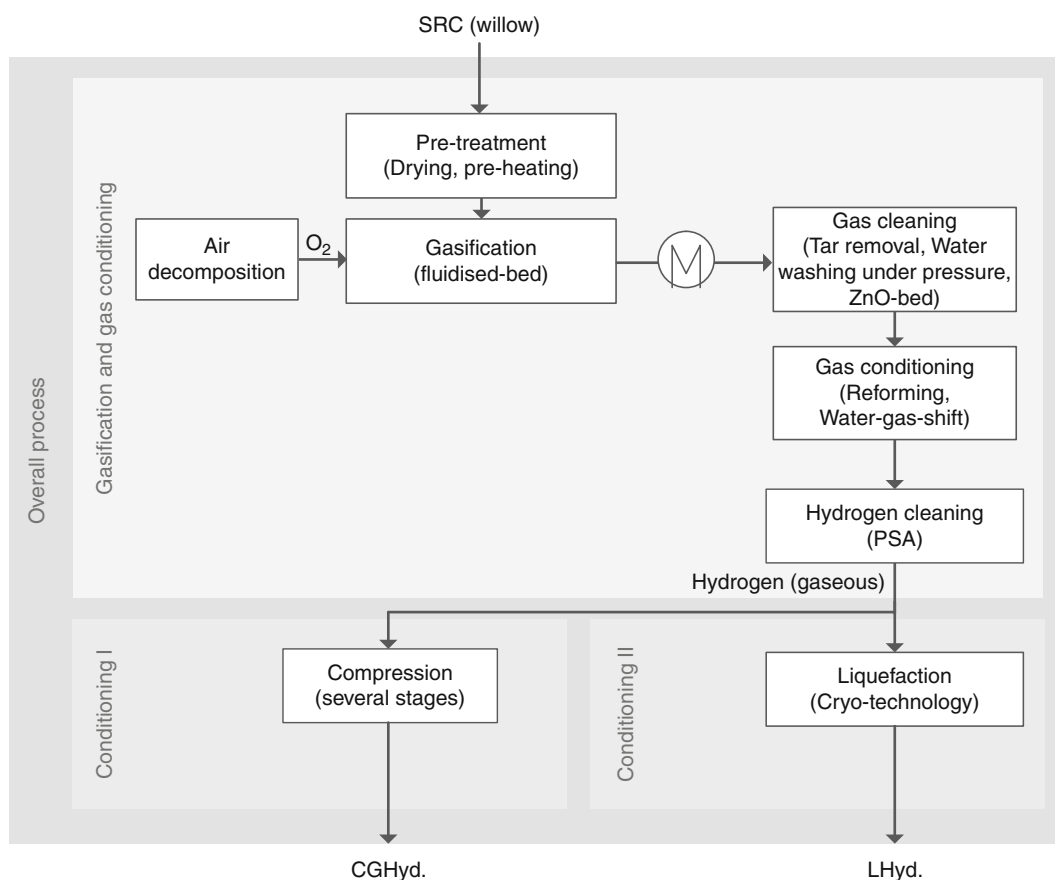
Regarding technology aspects, process steps such as biomass pretreatment, gasification, as well as gas treatment for synthesis are basically similar to that of the other discussed synthetic biofuel options. They have to be adjusted; especially the methanation requires high gas purity grades (nearly sulfur free gas) and a specific H_2/CO ratio.

At present, only the methanation of cleaned and conditioned gas out of coal is state of the art (e.g., SNG plant in US North Dakota with a capacity of 1.5 GW_{SNG} [29]). However, the methanation of gas generated out of biomass is under investigation in several test facilities and show up good results (e.g., energetic efficiencies of about 80%). For a fast and effective conversion, nickel- or copper-based catalysts are used for the exothermal methanation at a catalyst-specific temperature level of 200–450°C and pressures up to 50 bar. For managing the heat, currently several reactor concepts are in use or under investigation: (1) multiple fixed-bed reactors in one row with intermediate cooling or (2) fluidized-bed reactors with internal heat exchangers. Another heat management option is to recycle cold gas and to refeed it into the methanation [30]. The methane content after methanation is in a range of approx. 40–45 vol.%.

For bio-SNG upgrading to biomethane, basically the same is valid as shown for biogas upgrading. However, for CO_2 separation, typical large-scale technologies such as physical absorption processes (e.g., Selexol, Rectisol) and amine scrubber are applicable. Pressure swing adsorption can be used for final gas drying.

Biohydrogen

Hydrogen is basically used as raw material in chemical industries. Due to increasing environmental requirements and consumption of this industry (especially petrochemistry and refineries), the worldwide hydrogen demand is forecasted to increase annually with 5–7% [31]. While currently hydrogen is produced from fossil fuels, in the long run, renewable sources



Biofuels: A Technical, Economic and Environmental Comparison. Figure 8
Principle of thermochemical biohydrogen production

need to be the fundament of hydrogen production. Thereby the hydrogen production via thermochemical biomass conversion (Fig. 8) seems to be one promising perspective. At present, this process is under investigation at the state of pilot plants [32].

Also for hydrogen production, the various process steps (such as biomass pretreatment, gasification, and gas cleaning) are similar to that described above. However, gasification and gas cleaning have to be adjusted to generate a hydrogen-rich gas.

Within the conversion of biomass into hydrogen, no synthesis step is needed. Thus, the gas conditioning to increase the hydrogen content of the producer gas is quite important. For this purpose, two process steps can be applied: (1) an optional reforming step (e.g., via an endothermic steam reforming or an

autothermal reforming) and/or (2) a water–gas shift step. During water–gas shift reaction, part of the CO are converted into H_2 and CO_2 by addition of water-steam [33, 34].

In general, the first subsequent gas cleaning step is the water removal through condensation. In the following, the gas is cleaned by pressure swing adsorption (PSA). The PSA uses the different partial pressures of the gas components to adsorb undesired components. Remaining tail gas can be used for the process heat supply [35, 36].

For the final use of the produced hydrogen, the energy density has to be increased. For this purpose, there exist two common possibilities: (1) multistep hydrogen compression from about 13 to 30 bar to at least around 250 bar and (2) hydrogen liquefaction to

a higher density at final temperature of -253°C and a pressure of 1.2 bar by cryogenic procedures with an energy demand of 10 kWh/kg_{H2} [37].

System-Technological Assessment

Based on the technology characteristics, the biofuel options outlined above are compared based on criteria regarding biofuel production (i.e., stage of development, technical effort in terms of system complexity, expected plant capacity, and overall efficiency) and criteria regarding infrastructure and end use in vehicle fleets. With regard to European conditions, a summary is shown in Table 1.

According to Table 1, each biofuel option shows different benefits and bottlenecks along the overall production pathway. Conventional biofuel options

are already established technologies and hold a certain market share. Most of the future options are in a pilot (i.e., bio-SNG) or demonstration (i.e., lignocellulosic ethanol) phase, with only advanced biodiesel and bio-gas being already commercially available. Future options are linked to upscaled plant capacities that would allow benefiting from economies of scale and thereby balance the increased capital investments; in return, however, such large facilities pose logistical complexities in terms of biomass supply, storage, and handling. Furthermore, all synthetic fuels are linked to increased technical complexity, due to the various steps for their production (i.e., gasification, gas cleaning, synthesis), a fact which also reflects to the final overall efficiency of the processes.

Considering infrastructure, lignocellulosic ethanol has the advantage of the same treatment steps following

Biofuels: A Technical, Economic and Environmental Comparison. Table 1 Comparison of biofuel-specific system technology aspects

Biofuel option	Biomass conversion to biofuel				Infrastructure and use of biofuels		
	Current state of technology	Technical effort ^a	Plant capacity ^b	Overall efficiency ^c	Availability distribution	Blend to fossil fuels	Availability vehicles
<i>Conventional</i>							
Biodiesel	+++++	++++	++++	+++	+++++	++++	++++(+)
Bioethanol	+++++	+++	+++	++(+)	+++	++++	++++(+)
<i>Future</i>							
Advanced biodiesel	++++	+++	++	+++(+)	+++++	+++++	+++++
Bioethanol (lignocelluloses)	+++	++	++(+)	++	+++	++++	+++(+)
Biomethane/biogas	++++	+++(+)	++(+)	+++	+++	+++++	+++(+)
FT fuels	++	+	+	+(+)	+++++	+++++	+++++
Biomethanol	+(+)	++	++	++	++	++	++
Dimethylether	++	++	++	++	+	+	++
Biomethane/bio-SNG	++	++	+++	+++	+++	+++++	+++(+)
Biohydrogen	+(+)	++	++	++	+	+	+

Legend: +++++ very promising, +++ promising, + unfavorable

^aIn terms of complexity of biofuel production (i.e., from biomass treatment to final product)

^bIn terms of biomass input and flexibility regarding capacity as indicator for suitable plant locations

^c(Concept-specific) energetic net efficiency (base current development stage, theoretical considerations)

fermentation like conventional bioethanol (i.e., distillation, purification); therefore, its production could be established adjacent to existing ethanol facilities. Advanced biodiesel and Fischer–Tropsch diesel show very good technical properties that allow them to be blended at any percentage with conventional diesel without the need for modifications. From that point of view, they are considered very promising in terms of infrastructure suitability. This applies also to the biomethane options since both a natural gas grid is already broadly in place and natural gas vehicles are continuously increasing their fleet. The least promising option as it appears from Table 1 is biohydrogen, which requires both high technical effort in terms of production and special vehicle infrastructure (i.e., fuel cells).

Economic Assessment

With regard to requirements for a successful market implementation of future biofuel options, the consideration of economic aspects include the investigation of capital investment requirements, biofuels production costs, and well-to-wheel costs (WTW) at European conditions. This is done for the different future biofuel options in comparison to costs for the conventional biofuels (i.e., biodiesel and bioethanol).

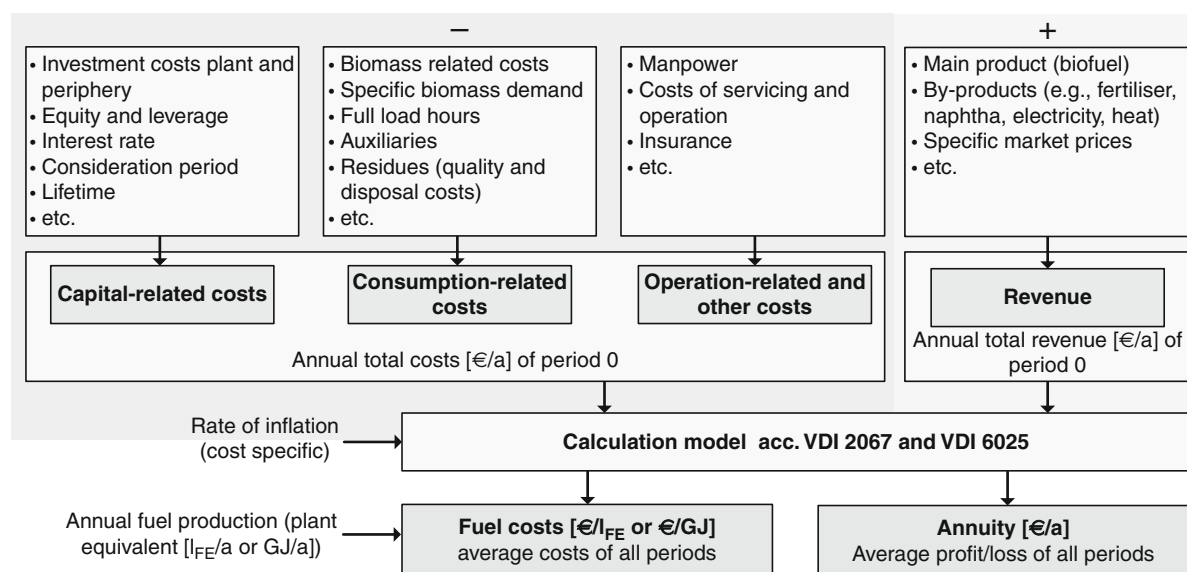
Basic Approach

Typically, economic assessment is aimed to compare different cost alternatives in order to identify relative advantages and determine important influencing factors. Especially with regard to assessing biofuel production costs, dynamic partial models (e.g., based on annuity) can be favorably applied since the accuracy is higher compared to static partial models due to a periodic accounting. The specific cost parameters relevant for biofuel production as well as the basic approach on the annuity model is presented in Fig. 9.

Capital Investment Requirements

Total capital investment (TCI) requirements of biofuels production plants are highly important with regard to financial risks on the one hand side and – as it is the case for more complex biofuel concepts – biofuel production costs on the other.

The determination of total capital investment costs is based on estimations (accuracy of approx. 20–30%) including the method of additional or overhead costs. According to this, plant equipment costs have been determined by up- or downscaling (typical scale factor of approx. 0.7) of existing costs data for similar devices. Moreover, component-specific installation factors



Biofuels: A Technical, Economic and Environmental Comparison. Figure 9

Model for cost calculation of biofuel production costs

(e.g., 1.54–1.66) have to be taken into account. For some components literature data are available; for some components (e.g., that are currently in pilot stage) only rough estimations of technology developers are available. The investment cost figures given were calculated with references from literature. An overview of rough estimations on total capital investment for future biofuel production plants is summarized in Table 2.

With regard to economy of scale, specific total capital investment typically decreases with increasing plant capacity. However, there is a continuous cost increase in the engineering and construction industries, which cannot be reflected at all. The price development of chemical plants and machinery (that also applies to biofuel production plants) is commonly indexed by means of the so-called Kölbel–Schulze methodology. According to this price index, the total capital investment for chemical plants has been increased by approx. 35% in the period from 2000 to 2007.

Biofuel Production Costs

Production costs of future biofuels have been analyzed for exemplary concepts at a database of the time horizon of 2005. The results are summarized in Fig. 10.

As the results of the economic analysis reveal, biofuel production costs show significant differences. Based on GJ fuel equivalent (FE), biomethane options (SNG and biogas) are the most favorable. The sensitivity analyses – carried out for the determination and optimization of cost components that influence the total biofuels production costs – show that feedstock costs (cf. Fig. 11), capital requirements, and the annual full load hours of the plant are strongly important.

Costs for conventional biofuels depend primarily on the prices of agricultural crops, which are relatively volatile and dependent on factors like climatic conditions, agricultural policies, intensification, and mechanization of production. On the other hand, future biofuel options may benefit from the use of residues but this advantage is partially outweighed from the increased supply costs and the more complex logistical aspects as well as the increased capital investments of large facilities. According to the fact that biomass supply depends largely on region-specific conditions, cost

for the provision of biomass to the plants can be from 10% to 60% of total biomass supply (i.e., production and provision) costs depending on the favorable location of the plant and the infrastructure to reach it.

It is expected that biofuel production costs will moderately increase in the future due to rising energy prices with expected price effects (e.g., opportunity costs for feedstock providers in the multi-sectoral biomass market) during broad implementation of biofuel strategies. Crude oil and natural gas prices will largely determine the economic competitiveness of biofuels against fossil fuels and set “limits” for feedstock costs above which biofuels cannot compete with conventional gasoline and diesel.

Based on literature and study survey, the bandwidth of available production costs of biofuel options is shown in Fig. 12. Also other studies show that no significant cost reduction for future biofuels can be expected compared to biofuels of the current generation.

Well-to-Wheel Costs

However, for a market implementation not only biofuel production costs but also total driving costs relating to WTW are of importance for end users. Therefore, with regard to the WTW biofuel costs involving costs of fuel distribution (i.e., via pipeline or tank) and vehicles costs of new private cars (i.e., in combustion and hybrid engines, fuel cells, here estimated referring to [39]), the following results (Fig. 13) can be indicated per vehicle kilometer.

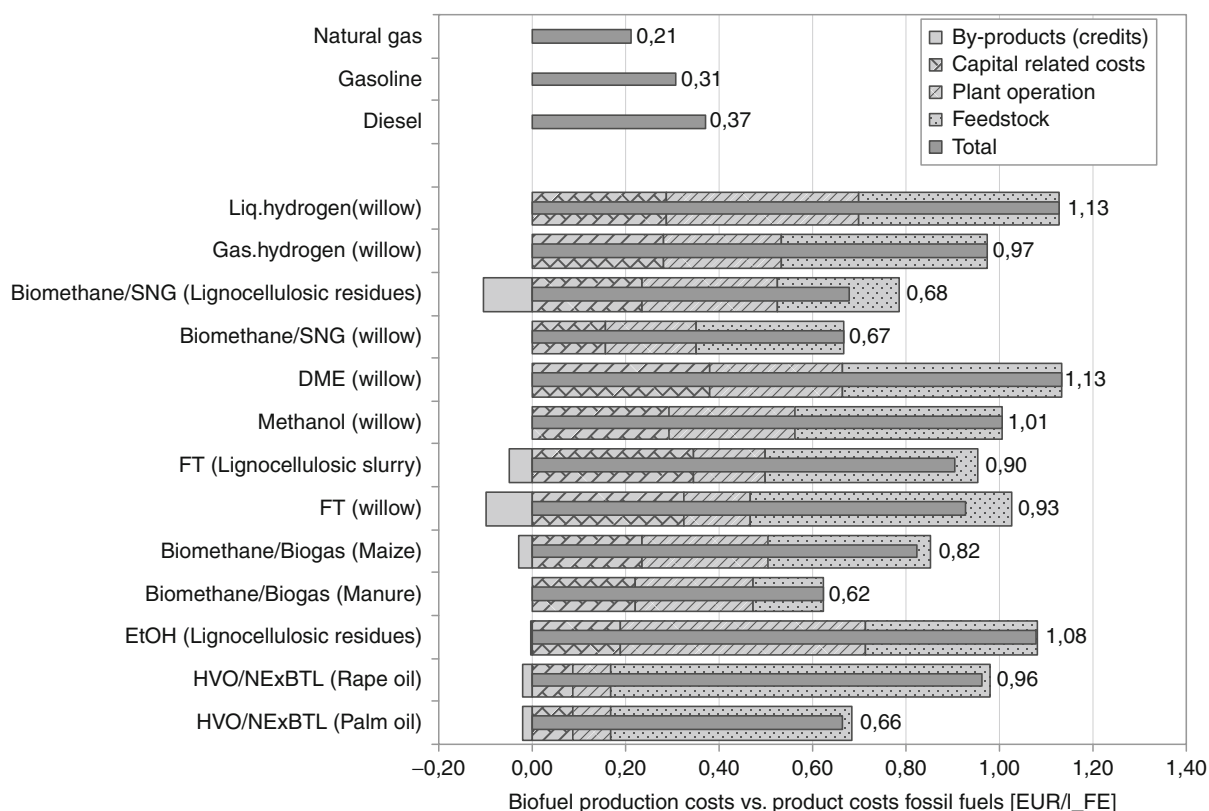
According to this, the differences in biofuel production costs will be lowered in terms of total driving costs as – except for fuel cell application – there is a similar cost range for all biofuels, primarily dominated by vehicle use costs. The costs for biofuel distribution play only a minor role. For a number of reasons (e.g., immature large-scale production), the biofuels of the future generation are significantly more expensive when compared to conventional oil-derived fuels such as diesel at total driving costs of approx. 0.33 €/km.

Environmental Assessment

The favorable political environment of the recent years has led to an increasing use of biofuels in the worldwide transportation sector. This development is mainly

Biofuels: A Technical, Economic and Environmental Comparison. Table 2 Overview of total capital investment for selected biofuel options (based on [6, 14, 16, 20, 38, 39])

Biofuel option	Basic plant equipment	Typical (expected) plant size (MW _{biofuel})	Total capital investment (mn EUR)	Specific total capital investment (EUR/kW _{biofuel})
<i>Conventional options</i>				
Biodiesel	Feedstock refinery, (trans)-esterification, biodiesel washing, by-product cleaning, and upgrading (e.g., glycerine, sulfates, methanol recovery), auxiliaries	4–190	0.9–65	190–340
Bioethanol	Feedstock pretreatment, hydrolysis/saccharification, fermentation, distillation/rectification, final upgrading, by-product treatment (e.g., DDGS, bagasse), auxiliaries	7–220	16–300	1,360–2,290
<i>Future options</i>				
Advanced biodiesel	Feedstock refinery, hydrogenation, product separation, auxiliaries	105–1,030	>100	390–470
Bioethanol	Feedstock pretreatment, hydrolysis/saccharification, fermentation, distillation/rectification, final upgrading, by-product treatment (e.g., lignin), auxiliaries	15–185	30–325	1,800–2,000
FT fuels	Feedstock pretreatment (e.g., mechanical, pyrolysis, torrefaction), gasification, gas cleaning and conditioning, FT synthesis, FT upgrading (e.g., hydrocracking), by-product treatment (e.g., naphtha), auxiliaries	>130–220	430–1,000	2,300–3,480
Biomethanol	Feedstock pretreatment, gasification, gas cleaning and conditioning, methanol synthesis, product upgrading (e.g., separation), auxiliaries	126–270	232–330	1,200–1,800
DME	Feedstock pretreatment, gasification, gas cleaning and conditioning, DME synthesis, product upgrading (e.g., distillation), auxiliaries	130–340	290–350	1,030–2,200
Bio-SNG	Feedstock pretreatment, gasification, gas cleaning and conditioning, methanation, final gas upgrading, auxiliaries	23–170	30–170	1,000–2,100
Biomethane/biogas	Feedstock pretreatment, digestion, final gas upgrading, auxiliaries	5–15	7.5–23	1,500–3,000
Biohydrogen	Feedstock pretreatment, gasification, gas cleaning and conditioning, final upgrading, auxiliaries	140–450	220–450	1,000–1,600



Biofuels: A Technical, Economic and Environmental Comparison. Figure 10

Exemplarily biofuel production costs vs. fossil fuels (refinery product costs)

driven by concerns about the security of energy supplies and the intention to mitigate anthropogenic greenhouse gases (GHG). However, recently, the sustainability of a broad biofuel production and use has been strongly questioned.

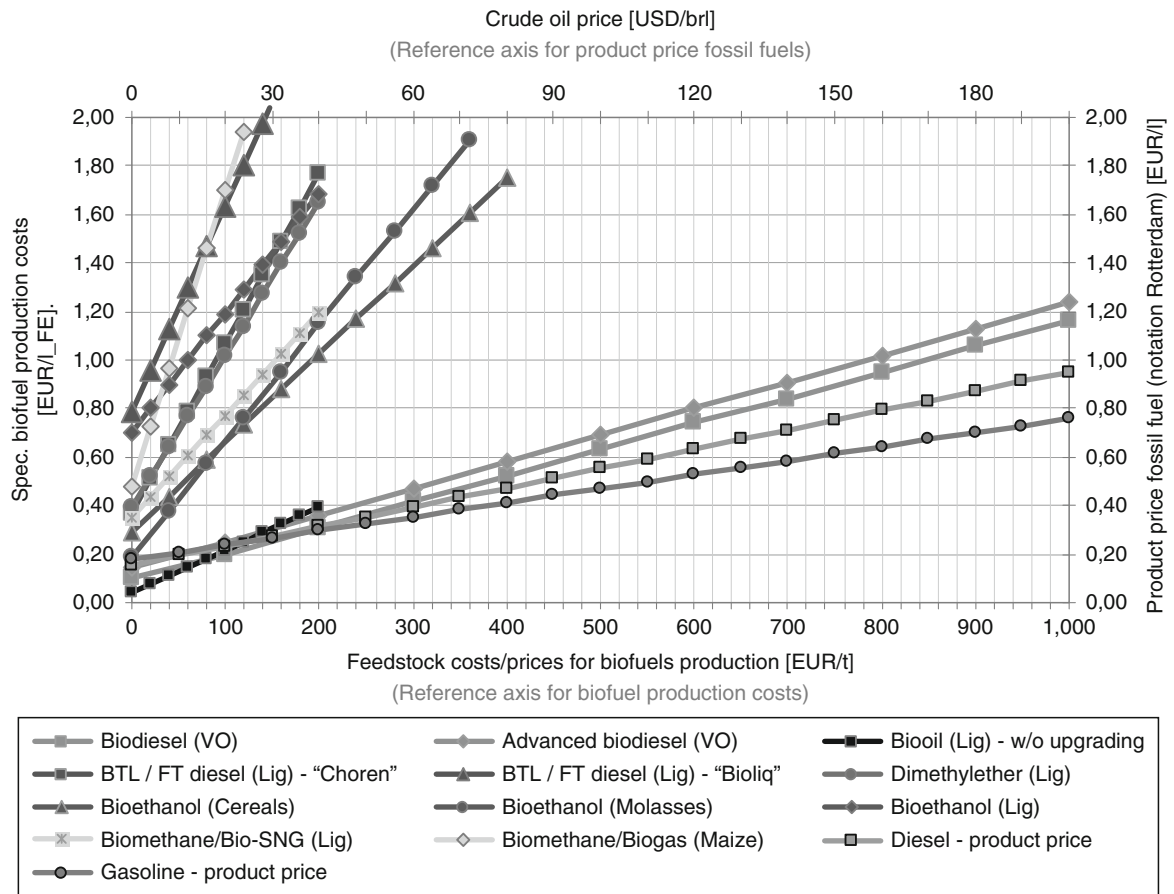
To secure especially the reduction of GHG emissions due to the use of biofuels in comparison to fossil fuels and a general sustainability of a broad biofuel production, an expanding biomass usage should also always follow certain sustainability criteria. Next to the environmental impacts related to the biofuel production and usage itself, these criteria should also cover aspects such as biodiversity, the conservation of ecosystems, or the protection of natural safeguards.

As an additional aspect, it is obvious that an increasing use of bioenergy together with a rising demand for food might result in an expanding pressure

on limited land resources. A possible consequence of this development could be the displacement of food production caused by the use of arable land for bioenergy production or an expansion of agricultural production (due to the constant demand for food and feed) into areas not previously used for crop production. Such a development might have direct and indirect effects. While the so-called direct land use change emissions can be calculated and related to a certain biofuel, the quantification of indirect effects is even more complicated.

Within the international context, potential environmental impacts of products (e.g., biofuels) or services (e.g., driven kilometer) are often analyzed with the help of a so-called life cycle assessment (LCA).

Most of the available LCA studies for biofuels focus on the environmental impact categories global warming effect and the primary energy demand.



Biofuels: A Technical, Economic and Environmental Comparison. Figure 11

Exemplarily biofuel production costs depending on feedstock costs and in comparison to mineral oil fuel product costs (typical bandwidth approx. feedstock prices: vegetable oils 600–1,200 €/t, cereals 100–250 €/t, molasses 10–120 €/t, wood 50–150 €/t, straw 0–90 €/t, maize silage 25–30 €/t, based on [6, 40, 41])

Below a brief insight on the basics of the LCA methodology and some exemplary results of existing LCA studies for biofuels are provided.

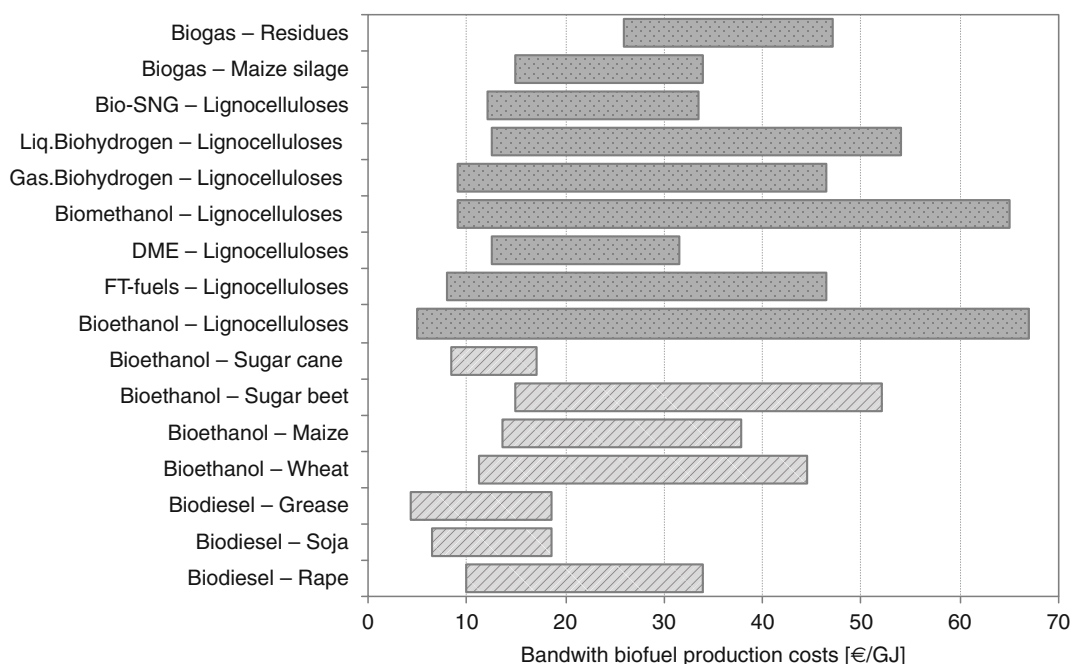
Basic Approach

The environmental performance of biofuels is often described by the LCA methodology. The LCA method is defined within the international standards ISO 14040 [50] and ISO 14044 [51].

Since the methodology of LCA aims to quantify potential environmental impacts throughout the production, use, and disposal of products, the system boundaries of this investigation are very broadly

defined. They generally comprise the overall product life cycle, starting with the extraction of raw materials ("from cradle") through to the utilization of the product and the disposal of all intermediate or waste products ("to grave"). The emissions linked to all production processes along the product life are considered. Most LCA studies that investigate potential environmental impacts of biofuel systems cover the whole supply chain of biofuels (Fig. 14).

According to the international standards ISO 14040 and ISO 14044, an LCA consists of four major iterative steps: (1) the goal and scope definition, (2) the life cycle inventory calculation, (3) the life cycle impact assessment, and (4) (result) interpretation.



Biofuels: A Technical, Economic and Environmental Comparison. Figure 12

Results of studies on biofuel production costs [39, 42–49]

The goal and scope of definition describes, among others, the underlying questions of the case study and the considered system boundaries and defines the so-called functional unit (e.g., 1 km driven). Additionally, the calculation procedure for the consideration of possible by-products is defined (e.g., allocation or substitution method).

In the life cycle inventory analysis, the inputs of resources, materials, and energy as well as the outputs of products and emissions are investigated and listed for each intermediate step of the production chain. After calculation of all input and output streams, it is possible to identify the amount of emissions related to the overall process chain (including emissions from the production and use of inputs materials and energies).

Within the phase of the life cycle impact assessment, the results of the inventory analysis are associated to specific potential environmental impact categories (e.g., global warming potential) with the help of characterization factors (e.g., the conversion of the different green house gas emissions (GHG) into CO₂ equivalent values using

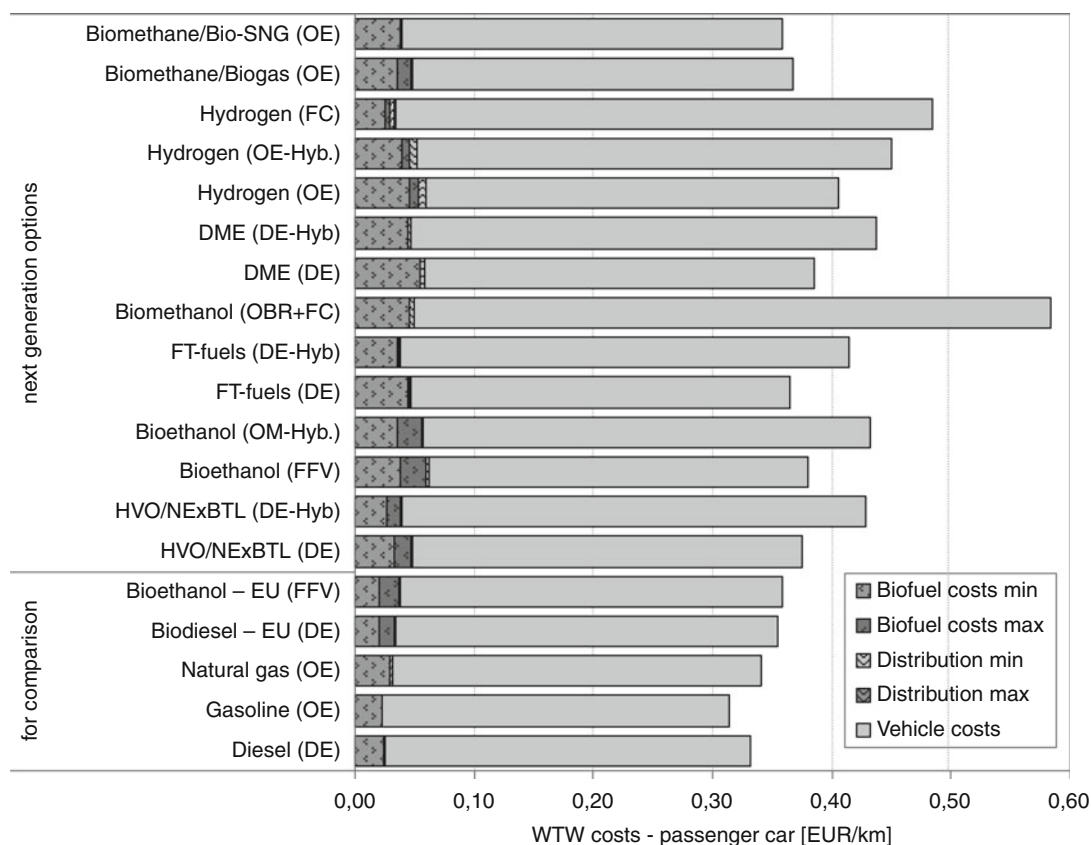
Intergovernmental Panel on Climate Change (IPCC) characterization factors).

The last phase of the LCA is the so-called interpretation phase. Within this phase, the results of the life cycle impact assessment are discussed and conclusions are drawn [50, 51].

Comparison of Existing Results

Most of the available LCA case studies for biofuels focus on the environmental impact categories global warming effect and primary energy demand. Some results published within the available studies that evaluated greenhouse gas (GHG) emissions per driven kilometer (passenger cars) for conventional and future biofuel options are shown in Fig. 15.

Most of the shown results have been calculated based on the approach of the ISO 14040 and ISO 14044 standard. Since this standardized method is very flexible to allow the assessment of all different types of biofuels under various circumstances and changing conditions, this flexibility can lead to



Biofuels: A Technical, Economic and Environmental Comparison. Figure 13

WTW costs (passenger cars) of different biofuel options

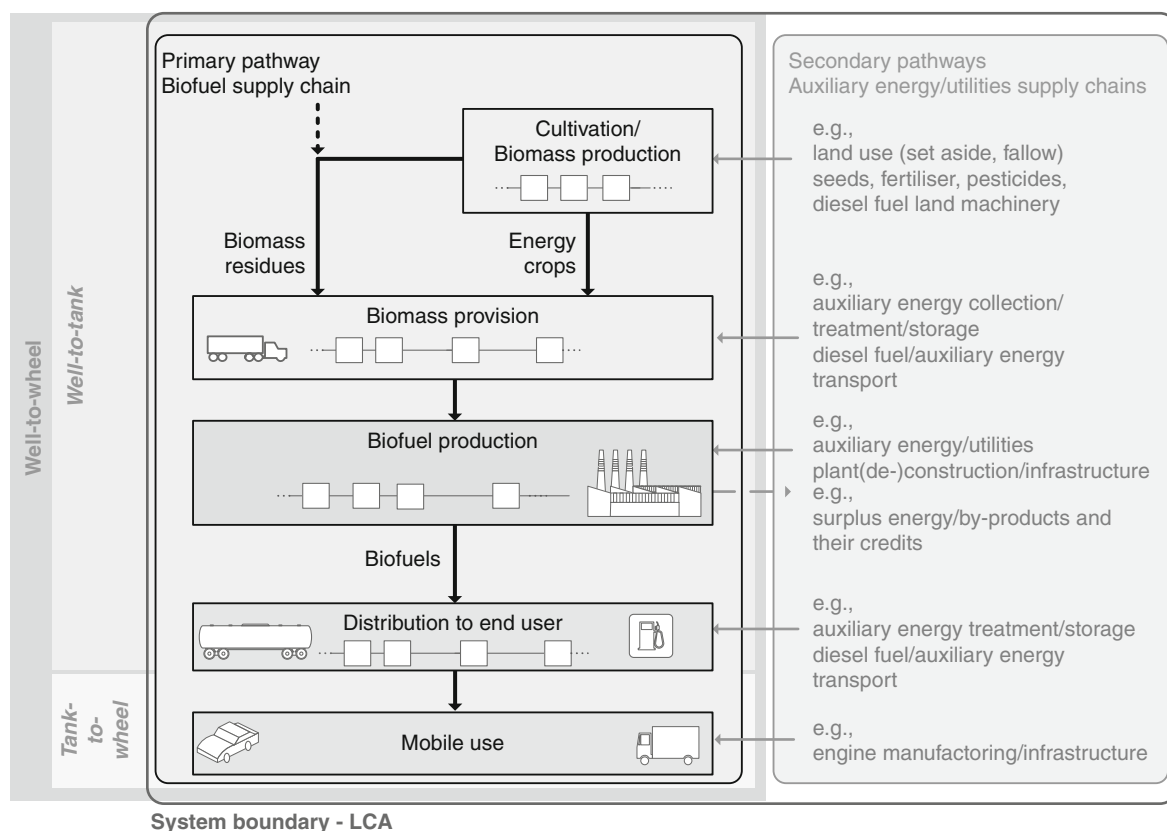
significantly varying results. As a consequence, the results from different LCA studies are in most cases very difficult to compare. This is also true for the results shown in Fig. 15.

As one can reveal there are partly large bandwidths of results for each of the different biofuel options. While current biofuel options show moderate GHG savings (in some cases the GHG emissions for biodiesel and bioethanol are even higher than for their fossil reference fuels), results for advanced and future biofuels show the tendency to increase the GHG mitigation potential. However, the results for the future biofuel options have been calculated for theoretical biofuel production concepts still to be demonstrated at commercial scale in most cases.

The main parameters influencing the total LCA result along the well-to-wheel chain are in most cases the production of biomass resources (especially for energy crops that, e.g., require mineral fertilization) as well as the biofuel production process (especially for concepts with a high demand for external process energy). Feedstock transport to the biofuel production plant as well as biofuel distribution and its use commonly show less negative impacts on the overall result.

Table 3 summarizes the main differences between current and future-generation biofuels with regard to the aspects of land use change and land use competition, feedstock cultivation, and nutrient cycle.

Up to now the majority of the available literature sources do not include effects and emissions from land



Biofuels: A Technical, Economic and Environmental Comparison. Figure 14

Example for an LCA system boundary to assess a biofuel production chain

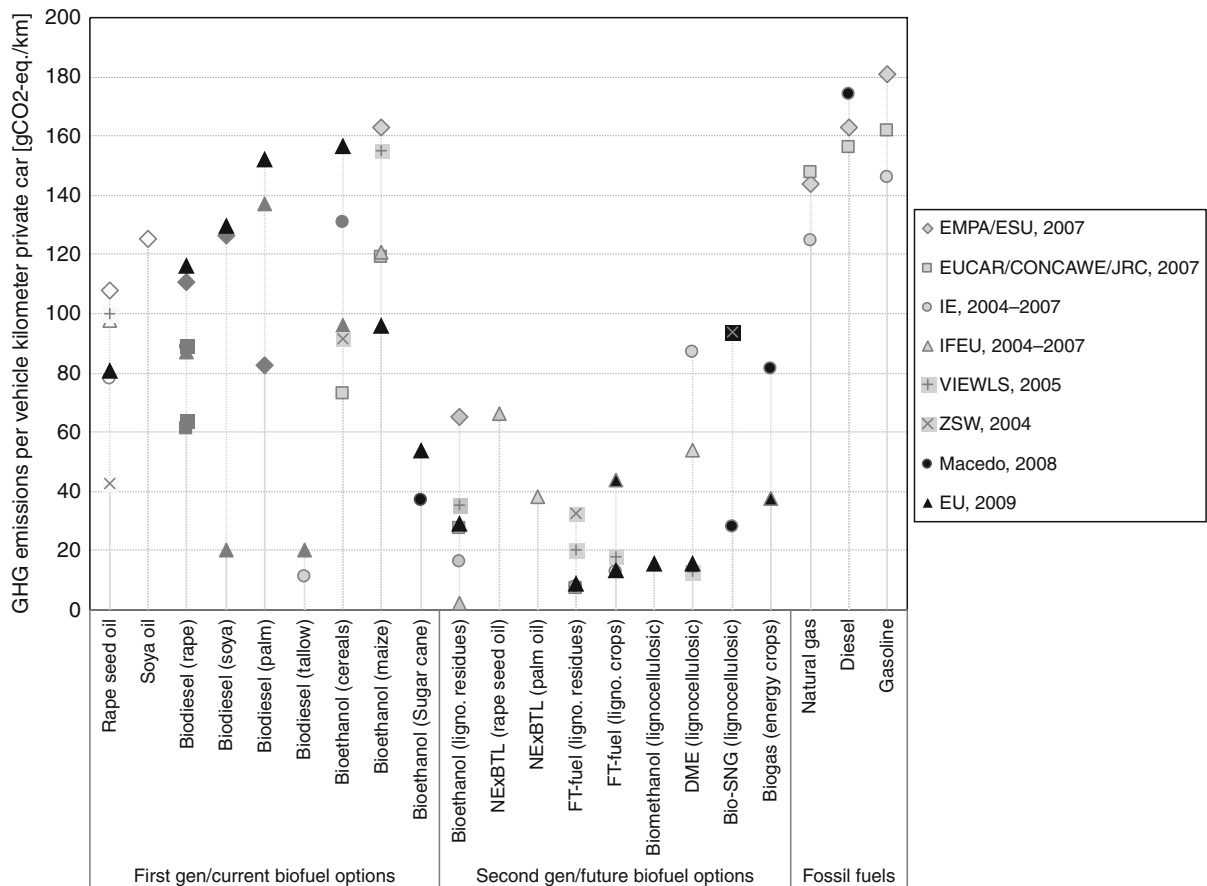
use change. Land use change can have an effect on the increase or decrease of carbon stored in the vegetation and the soil of the considered area. Therefore, especially the conversion of areas with a high carbon inventory such as primary forests into agricultural areas can lead to significant CO₂ emissions. The consideration of these effects within a life cycle analysis typically will result in negative results and thus in decreasing potentials for GHG mitigation [57].

However, until now international support policies for transportation biofuels have made no or only minor differentiation according to how they have been produced (e.g., regarding environmental impacts). Thus, some governments partly support biofuels that have a higher negative environmental impact than the substituting fossil product. To ensure at least a minimum level of sustainability requirements

for the production and use of biofuels, the European Union introduced different sustainability requirements and standards for biofuels defined within the recently published European Renewable Energy Directive (2009/28/EC). This directive includes standards for a sustainable production of the biomass needed for the biofuel production as well as requirements for a mandatory minimum GHG mitigation. According to this, GHG saving targets or at least a minimum GHG saving for different types of biofuels will be a mandatory requirement at a national and/or European level in the future.

Conclusions

Overall, current biofuels will only provide a niche market (mainly covered by bioethanol and biodiesel



Biofuels: A Technical, Economic and Environmental Comparison. Figure 15

Literature results for GHG emissions (based on EMPA 2007 [52]; EUCAR, 2007 [39]; IE 2004–2007 [53]; IFEU 2004–2007 [12, 46]; Viewls [49]; ZSW 2004 [54]; Macedo 2008 [55]; EU 2009 [56])

until 2020). It is uncertain when next-generation biofuels will be a viable alternative and when significant production can be expected. It is certain that next-generation biofuels firstly will enter the market in the EU or the US before being introduced within developing countries. However, biofuels and bioenergy more generally have to increase in relevance in future in order to meet the energy and environment requirements in an efficient way. It is important to analyze and assess the real potentials of biofuels under consideration of region-specific frame conditions and sustainability criteria, since no biofuel option is suitable for all regions at all.

From a technical point of view, each biofuel option shows different benefits and drawbacks. Thus there is no silver bullet for biofuel; each of them needs to be considered with regard to available feedstock, surrounding available infrastructure, and demand of the market. Current options like bioethanol from sugar and starch as well as conventional biodiesel from oil crops and animal fats are market mature. Options like advanced biodiesel (HVO) and biomethane via biogas enter the market. And production concepts for biofuel option of the future generation are currently in laboratory (e.g., biohydrogen) to pilot and demonstration stage (e.g., bioethanol, Fischer–Tropsch fuel, dimethylether, and bio-SNG). Thus, further R&D&D is required with

Biofuels: A Technical, Economic and Environmental Comparison. Table 3 Main differences regarding environmental impacts of current and future biofuels

Issue	Current biofuels (first generation)	Future biofuels (second generation)
General database	Database on biofuel value chains are available based on practical experiences	Only limited database on biofuel value chains since they have not been demonstrated in practice at present, most of applied data background is based on theoretical concepts
Land use change/land use competition	Land use change has taken place	Potential of land use change, for example, from degraded land to arable land
	Feedstock cultivation on arable land that increase land use competition with food and fodder production	Potential feedstock cultivation (e.g., of perennials) on land which is not suitable for conventional agriculture; decrease of land use competition
		However, land is bounded for several years when applying perennial cropping
Cultivation	Intensification due to increased use of fertilizer and pesticides as well as increased use of water; thus, higher environmental implications	Potential decrease in cultivation due to decreased used of fertilizer, pesticides and water; thus, potential to lower environmental applications
Nutrient and humus cycles	By-products (e.g., straw, press cake, glycerine, fertilizer, DDGS) can be used for farming; thus, potential of closed nutrient and humus cycles	Use of the whole plant for biofuel production may lead to additional expenditures to achieve an well-balanced nutrient and humus cycle
		Usually no by-products that can be applied within the agricultural sector

regard to (1) further development and use of promising biofuel concepts in practice, (2) upscaling to medium- and large-scale plants, (3) the use of approved system components and demonstration of efficient interaction, and (4) plant operability and reliability. For a successful market implementation, existing techno-economic barriers have to be overcome and capital risks need to be minimized.

From an economic point of view, biofuels have so far required state support in order to be cost competitive with current fossil fuels. Feedstock production costs and their dependence on energy prices and climatic conditions are the factor that influences production costs of current biofuels the most (up to 70%). For future biofuels, these costs will play a smaller role, if residues and waste are used as feedstock but the supply and handling of large amounts to upscaled facilities will increase the complexity of logistics and balance this

advantage. On the other hand, dedicated cultivation of lignocellulosic feedstock like short rotation forestry will again add up to the feedstock production and supply costs. Furthermore, the large capital investment associated with large plant sizes increase the risk of investment; therefore, economic viability will require the identification of an ideal location where a secure market for the product and a long-term continuous supply of feedstock can be guaranteed. In addition to that, complex conversion procedures (e.g., simultaneous C5 and C6 fermentation) increase the operating costs and subsequently total production costs. For all these reasons, future-generation biofuels are not expected to be cost competitive at least in the short term. However, ongoing research and development is expected to reduce the conversion costs and allow production in large commercial scale that would allow benefiting from economies of scale.

From the environmental point of view, all biofuels need to be analyzed and assessed regarding their environmental impacts. The political introduction of sustainability criteria for the production and use of biofuels, including minimum GHG mitigation threshold values could lead to a promotion of biofuels with favorable GHG footprints. Concerning these aspects, especially future biofuel options based on lignocellulosic feedstock or residues seem to be very promising. In general, it has to be noted that the current sustainability debate on biofuels is mainly focused on the impact category of global warming. However, an efficient and sustainable biofuel strategy should also consider other environmental aspects such as biodiversity and the protection of natural ecosystems.

Future Directions

An environmentally friendly transportation sector can only be realized by a combination of measures such as the development of new vehicle technologies, the provision of new infrastructure networks, and the application of alternative fuels. Nowadays, biofuels are the only way to substitute fossil fuels and contribute to the mitigation of greenhouse gas emissions within the transportation sector. For these reasons, their role is expected to increase, reckoning at the same time that fossil fuels will remain the dominant fuel option in the near future. Medium- and long-term research is focused nowadays to future-generation biofuels that use also residual feedstock and minimize problems associated with current generation biofuels. Some of these options are in a pilot or demonstration phase (e.g., lignocellulosic ethanol, biosynthetic fuels) and research funding in an international scale in areas like biomass gasification and gas cleaning, methanation, enzymatic hydrolysis of lignocellulose, simultaneous saccharification of C₅ and C₆ sugars will increase the potential for commercial application in the years to come. Other options like biohydrogen are closely linked to the development of vehicle infrastructure (e.g., fuel cells, batteries) and their implementation is interdependent. Similarly, electro-mobility that is surrounded with high hopes requires the development of both the vehicle fleet and the infrastructure network, a fact that places its implementation in the long term.

Of great importance within this context is that electricity is produced from renewable sources, so that electro-mobility actually makes a difference in the transport sector.

On the biomass supply side, future research will focus on the sustainable use of all residue and waste sources for the production of future-generation biofuels. This will be complemented by the sustainable use of land for large-scale production of lignocellulosic crops, such as short rotation forestry or miscanthus; this combination should be able to secure the continuous supply of future-generation facilities that require large amounts of biomass.

Considering sustainability of production and the biomass use itself, the goal for the future is to use the largest possible amount of the initial feedstock, in other words maximize the biomass use efficiency. For that reason, the concept of biorefineries receives nowadays increasing attention and is expected to be the focus of research in the future. Following the example of conventional refineries, biorefineries use biomass as feedstock and produce an array of marketable products by integrating processes and processing all product streams. These products include biofuels, feed, food, heat, electricity, chemicals, polymers, and others. The term “biorefinery” as such is recently introduced but certain facilities that have used this principle are known for years (e.g., pulp and paper mills). Nowadays, the term is expanded and used in a wider sense and a different number of biorefinery concepts have been introduced. Within this context, future goal is to integrate existing processes with new technologies and thereby increase the opportunities for a more efficient biomass use.

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Biofuels: Upgraded New Solids

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Article Outline

Glossary

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Glossary

Upgraded solid biofuel is a solid fuel, which is produced in a technical process, using biomass as feedstock.

Pelletizing is the process of compressing material into the shape of a pellet.

Briquetting is a process of forming briquettes or compacts under pressure with bigger and other sizes than pellets.

Torrefaction is a mild pyrolysis process performed at temperatures between 200°C and 300°C within an inert atmosphere.

Hydrothermal carbonization is a process for the production of a solid fuel in hot pressurized water.

Biocoal is a solid fuel produced by hydrothermal carbonization

Definition of the Subject and its Importance

For the energetic use of biomass, a number of combustion and gasification processes exist. Especially high efficient processes, often developed for the use of coal, have very strict fuel requirements. In many cases, “classical” solid biofuels (like wood logs, wood chips)

cannot fulfill the requirements of these conversion processes. The solution is the adaption of the fuel properties to meet the process requirement by a pretreatment step. The results are upgraded “new” solid biofuels suitable for highly sophisticated conversion processes.

A second driver for biomass pretreatment is the increased demand for biomass as a renewable energy carrier. Therefore it is necessary to utilize also organic mass streams with low quality, e.g., leaves, bark, straw, and hay. Biomass pretreatment alters the transport, storage, and handling characteristics of solid biofuels, as well as their combustion and gasification properties. In doing so, it enables enhanced utilization routes for lignocellulosic biomass resources. Whilst briquetting and pelletizing mainly adapt physical properties of the fuel, torrefaction and hydrothermal carbonization (HTC) also change chemical properties and produce a more coal-like solid biofuel.

Introduction

For the production of upgraded “new” solid biofuel, three main pathways are of major importance:

- Agglomeration as physical process including briquetting and pelletizing
- Torrefaction
- Hydrothermal carbonization as thermochemical processes

Although the products are comparable, the processes have completely different properties.

Briquetting is a well-known process where milled and often fine-particle biomass is compressed interfacially under high pressure. Pelletizing is a process with established technical equipment arising from the animal feed industry. By the end of the last decade, the process was adapted for the production of wood pellets. Today the pelletizing process is of great relevance for the development of alternative biomass pellets (i.e., agro-pellets).

Torrefaction is a mild pyrolysis process performed at temperatures between 200°C and 300°C within an inert atmosphere. Torrefied biomass contains typically 60–70% of the initial mass and 90% of the initial energy content (LHV). Benefits of torrefied biomass compared with green biomass are increased energy density and homogeneity, improved grindability, pronounced hydrophobic character, and enhanced reactivity.

The properties of torrefied biomass allow for the substitution of coal in existing gasification and combustion plants with low retrofitting requirements.

Hydrothermal carbonization is performed in pressurized hot water at 170–250°C using an acidic catalyst. The product is suspended in water resulting in additional efforts for separation and drying. Possible products of hydrothermal carbonization are either functional carbonaceous materials for a variety of applications or solid biofuels with properties similar to lignite.

The main historical keywords for the three pathways are:

- Agglomeration:
 - Briquettes are long-established upgraded solid fuels, especially based on coal.
 - 1970s: first small scale pellet heating units build in the USA.
 - Late 1970s: first pellet plants in Europe.
 - Middle/end of the 1990s: strongly increasing market importance.
 - Today: Wood pellets are a popular fuel for heating systems for households as well as for co-combustion in coal fired CHP-plants in various especially European countries.
- Torrefaction:
 - Last centuries: research on dry thermal upgrading of solid fuels based on charcoal and coke production.
 - Since the 1980s: scientific investigation of biomass torrefaction.
 - 1987: first commercial scale torrefaction plant by Le Bois Torrefie du Lot, a subsidiary of Pechiney (for economic reasons, the plant was decommissioned in the beginning 1990s).
 - Today: commercialization of first plants for pretreatment of biomass for co-firing, gasification, and pelletizing, as well as for better transportation and storage.
- Hydrothermal carbonization:
 - 1913: hydrothermal transformation of biomass into a coal-like product described by Bergius
 - In the 1920s, 1930s and 1960s: ongoing scientific investigation
 - Since 1995: development of a process for the hydrothermal use of waste biomass like sewage sludge by EnerTech (USA) and Mitsubishi (Japan)

- 2008: first pilot-plant employing the SlurryCarb™-process in Rialto, USA
- Today: investigation and commercialization of lower temperature hydrothermal carbonization especially in Germany

Pelletizing and Briquetting

Principles

Agglomeration is defined as a process that brings loose material (particles or fibers) together to agglomerated products with designated form and properties. Caused by the mechanical contact and the physical binding mechanisms a size enlargement compared to the original material is achieved whereas the free particle surface area is reduced. Usually, pressure agglomeration processes like briquetting and pelletizing are used to improve the mechanical and physical properties of solid biofuels. The main benefits of such a compressing are:

- Improvement of the flow, the dosing and conveying properties of the material
- Increase of the bulk density and for this reason reduction within the transport expenses
- Removal of the risk of solidification and bridging of fine bulk solids during transport and storage
- Decrease and removal of dust in the bulk good, reducing dust explosion risks
- Decrease of material loss and prevention of product losses, e.g., caused by oxidation and microbiological decomposition
- Stabilization and homogenization of heterogeneous mixtures of materials, e.g., for the development of blended pellets
- Improved thermal and combustion properties

Briquetting is a common process where milled and fine-particle biomass is compressed interfacially under high pressure. The friction between the material and the press mold releases heat, which activates the binding forces between the particles. The feasibility of briquetting depends on the plasticity of the biomass. The harder and more brittle the material is, the more binding agents are needed to form bridges between the particles. The addition of binding agents is mostly not required for biomass briquetting [1].

Pelletizing is another process for the agglomeration of biomass, where grinded biomass is compacted to pellets by pressure agglomeration. Similar to the briquetting process, the material needs to be plastic or deformable. Friction between the material and the friction channel leads to heat release responsible for the activation of binding forces. Additionally, the material needs an adequate moisture content, which in the easiest case can be achieved by adding water.

Depending on the feedstock and the agglomeration process different binding mechanisms and forces are relevant for the adhesiveness of individual particles (Fig. 1). The understanding of these binding mechanisms during pressure agglomeration is important since optimal particle and fiber bonds in agglomerates cause good physical and mechanical properties. Major binding mechanisms are [2–4]:

- Solid bridges caused by sintering, partial melting, chemical reaction, recrystallization of dissolved substances, hardening binders etc.
- Adhesion and cohesion forces by non-free-moving liquids, highly viscous binders, and adsorption layers (<3 nm thickness)
- Adhesion, surface tension, and capillary pressure by free-moving liquids in pendular, capillary, or funicular state

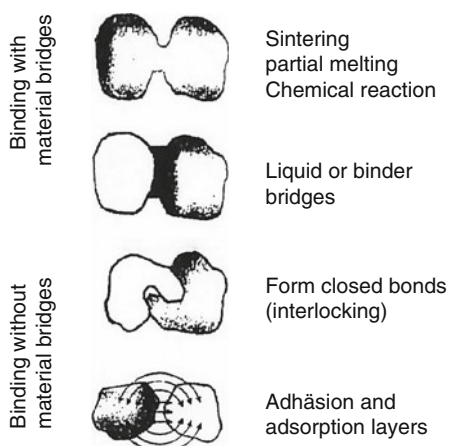
- Attraction forces between solids – molecular forces like van der Waals forces, free chemical bonds and associations
- Interlocking bonds

The agglomeration of fiber material like wood and herbaceous biomass is mostly based on interlocking bonds. Caused by pressure agglomeration the fibers twist, weave, and bend around each other forming a kind of mesh. Additionally, the formation of interlocking bonds is favored because of the high pore volume. Agglomerates like woody and herbaceous pellets, which mainly stick together by interlocking bonds and which are formed by pressure agglomeration, do not require the use of binding agents during the agglomeration process. However, binders reduce the abrasion of dies as well as the energy consumption. Therefore they are often used.

If the binding strengths achieved by the agglomeration process are too weak, the particle sizes are too large, or certain agglomerate characteristics have to be obtained, additives can be used. Additives are solid or liquid materials causing additional bindings through solid bridges or adhesion forces.

Low viscous liquids like water, which is the cheapest and most common additive, are motile and adsorb on the surface of the particles. If the proportion of the liquid is small, individual liquid bridges develop between the particles. The more fluid disperses between the particles, the higher the cohesion of the agglomerate becomes caused by the capillary pressure. Therefore, steam is used to produce liquid bridges forming solid bridges during the cooling process. Furthermore, steam preheats the material and increases the moisture content. This reduces the energy demand and provides higher stability [5, 6].

However, each process and material requires different moisture levels since too high liquid contents decrease the quality of the agglomerates. In contrast to these mechanisms, binding agents with a high viscosity (like molasses) inhibit the formation of capillary forces. Adhesion forces between the particles and the binding agent are formed instead. Since these forces are more intense, the agglomerates can be more strained. Additionally, binding agents can form solid bridges [4, 7]. Binding agents commonly used in wood pelletizing are wheat, maize starch, and thermally treated starch flour [1].



Biofuels: Upgraded New Solids. Figure 1
Illustration of selected binding mechanisms [4]

Pelletizing and Briquetting Processes

Agglomeration processes consist of individual process steps largely similar for the production of either briquettes or pellets. Figure 2 presents the entire process chains involving several biomass conditioning and post treatment steps.

The pressure agglomeration itself is achieved by applying external forces to particles in different shaped dies to form enlarged agglomerates. Table 1 provides an overview of established technologies.

Briquettes are fabricated either by punch-and-die presses or by extrusion presses. Pelletizing is usually done with roller presses. These roller presses can be subdivided in presses with one or two rollers. Double-roller presses have been originally developed for the agglomeration of coal and are often used for finely divided solids. Because of the low retention time and temperatures non-biomass briquettes can be produced with these presses. The industrial production of wood pellets mainly uses roller presses generally operating with tree rollers; they are called pellet mills or pellet machines.

Properties of Biomass Pellets and Briquettes

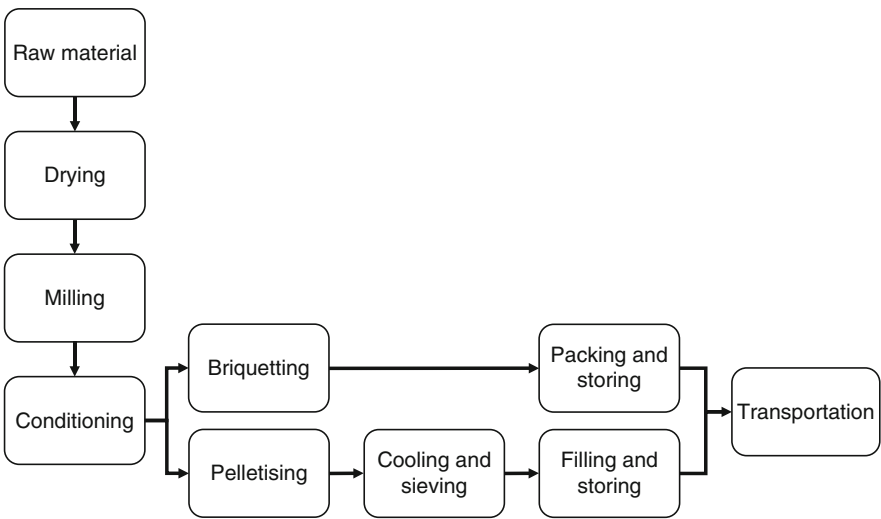
To utilize biomass as a fuel, the chemical properties and the properties like heating value and water and ash content need to be well known. Besides these mass-specific properties, the mechanical-physical properties,

which can be influenced by the compaction process, are of importance (Table 2). Furthermore, these properties are used to evaluate the quality of a compaction process and of the produced pellets and briquettes.

Besides these properties, the physical properties of the raw material like the particle size distribution and the water content influence the quality of the compaction process. Therewith they influence the quality of the compressed fuels similarly to the compaction process.

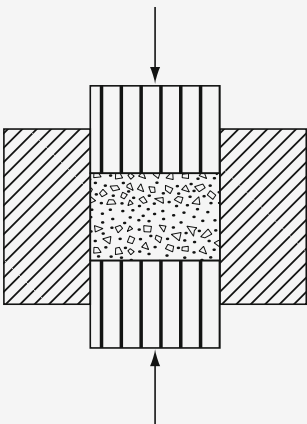
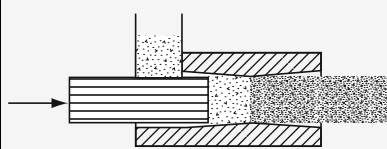
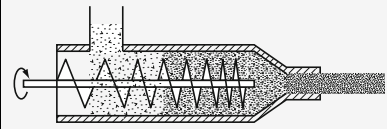
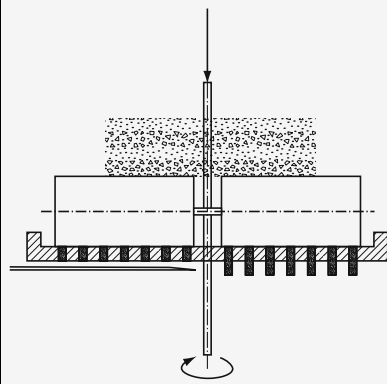
Caused by their great relevance for combustion processes, the mechanical and physical properties of solid biofuels are standardized, like for wood pellets and briquettes in DIN 51731, DIN plus, or ÖNORM M 7135 (Table 3). Currently these values and standards are adapted on EU level in EN 14961 and its quality standards. Besides wood, the standard will also include values for nonwoody biomass pellets not regulated so far. Additional standardization activities have been carried out in some EU countries (like Austria) developing pre-standards like ÖNORM C 4000 for compressed Miscanthus and ÖNORM C 4002 for compressed straw (Table 4). These values are considered to evaluate the quality of briquettes and pellets produced out of other raw materials, like different straw types, hay, and rape press cake (Tables 5 and 6).

The required properties of the above-mentioned standards can be kept if the production process is

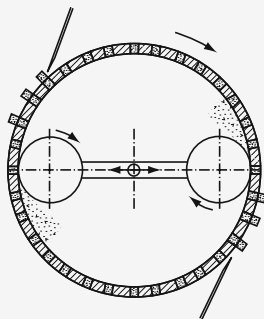


Biofuels: Upgraded New Solids. Figure 2
Production process of pellets and briquettes

Biofuels: Upgraded New Solids. Table 1 Classification of agglomeration processes according to their active principle

Punch-and-die press [8, 9]	
	– Material is compressed with high pressure in closed and differently formed dies
	– One or two punches are possible, usually one punch from above with variable travel
	– Pressure induced hydraulically
	– Low friction, no cooling required
	– Briquettes often rectangular, stackable
Ram extrusion press [8–10]	
	– Material pushed towards a cylinder by a ram
	– Loose material is punched against already initially compressed material
	– Compression and re-expansion leads to plastic deformation
	– Good adjustment of back pressure and friction
	– Briquettes round or of orthogonal profiles
	– suitable for elastic materials
Screw extrusion press [8, 11]	
	– Compression by single- or double-screw extruders where the pressure is generated by decreasing the screw thread
	– Allows high briquette qualities
	– High frictional resistance, higher energy consumption
	– Shape of the briquettes depends on extruder
	– common for animal feed pellets
	– Feed enters the press from above, falls down by gravity and is diverted evenly to the rollers and the track of the die
	– Even material densification, uniform extrusion
	– Pellets are homogeneous
	– Length adjustment by cutters underneath the die

Biofuels: Upgraded New Solids. Table 1 (Continued)

Pellet mill with ring die and press rollers [8, 13–15]	
	– Principle similar to pellet mills with flat dies
	– Ring die is driven
	– Material enters from the front side of the ring
	– Paddles or adjustable plows and three rollers are used to deal with uneven material
	– Internal rollers are moved by the continuous flow of feeding material inside the pellet mill.
	– State-of-the-art for wood pellets

Biofuels: Upgraded New Solids. Table 2 Mechanical and physical properties of compressed fuels with effects to combustion

Parameter	Role in compaction process	Influence on combustion system
Dimension	Regulated by the dimension of the pressing tools	Dimensioning of the feeding system of combustion plants
Gross density	Besides the durability an important measure to evaluate the quality of compacts	With higher particle densities the burnout rate might be increased
Bulk density	Dependent on the quality of the compaction process	Is increasing with increasing gross density; The higher the bulk density the higher the energy density of the biofuel
Amount of fines	Dependent on the quality of the compaction process	Fines cause problems in the combustion process and cause higher dust emissions during transport and handling
Durability	Typically used to evaluate the quality of produced pellets and briquettes (strength, amount of fines)	Risk of failures according to blocking and ash melting by fines

known. However, according to the raw material, the milling grade, and morphological characteristics, the compaction process can be difficult. Nevertheless, the mechanical and physical properties are not directly depended on the raw material. Crucial are the preprocessing of the raw material as well as the process parameters and control of the compaction.

Influencing Parameters for Biomass Pellets and Briquettes

The pellet quality is influenced by several parameters [9, 13, 19]. The raw material composition has the most

severe influence on quality parameters like mechanical durability, bulk density or gross density, followed by the type of conditioning (e.g., preheating and addition of steam), and the milling technology (i.e., particle size and type of mill). The influence of the type of compaction is slightly smaller. Significantly lower is the influence of the cooling after the compaction process.

Raw Material and Raw Material Composition A wide variety of biomass can be used as raw material for the production of solid biofuels (e.g., energy crops like miscanthus, switchgrass and wood from short

Biofuels: Upgraded New Solids. Table 3 Values for mechanical and physical properties of the biofuels standard ÖNORM M 7135 “Compressed wood and compressed bark in natural state: Pellets and briquettes^a”

Parameter	HP1 Wood pellets	HP2	HP3 Wood briquettes	RP1 Bark pellets	RP2	RP3 Bark briquettes
Diameter D (mm)	$4 \leq D < 10$	$10 \leq D < 40$	$40 \leq D < 120$	$4 \leq D < 10$	$10 \leq D < 40$	$40 \leq D < 120$
Length (mm)	$\leq 5 \times D$	$\leq 4 \times D$	≤ 400	$\leq 5 \times D$	$\leq 4 \times D$	≤ 400
Gross density (kg/dm ³)	≥ 1.12	≥ 1.10	≥ 1.10	≥ 1.12	≥ 1.10	≥ 1.10
Bulk density (kg/m ³)	–	–	–	–	–	–
Mechanical durability (wt.-%)	≥ 97.7	–	–	≥ 97.7	–	–
Fines < 3.15 mm (wt.-%)	–	–	–	–	–	–
Binders/lubricants (wt.-%)	≤ 2	≤ 2	≤ 2	≤ 2	≤ 2	≤ 2

^aWood and bark pressings are of various shapes and sizes. This includes the classes HP1 (wood pellets), RP1 (bark pellets) and HP3 (wood briquettes), RP3 (bark briquettes). HP2 and RP2 have sizes which are between pellets and briquettes: it depends on the type of agglomeration process.

Biofuels: Upgraded New Solids. Table 4 Values for mechanical and physical properties of the biofuels standards for compressed miscanthus and straw

Parameter	ÖNORM C 4000		ÖNORM C 4002	
	Compressed miscanthus		Compressed straw	
Fuel type	Pellets	Briquettes	Pellets	Briquettes
Diameter D (mm)	$6 \pm 1, 8 \pm 1, 10 \pm 1$	$\leq 60, \leq 100$	$6 \pm 1, 8 \pm 1, 10 \pm 1$	$\leq 60 \leq 100$
Length (mm)	$\leq 30 \leq 35 \leq 40$	$\leq 50 \leq 100 \leq 300$	$\leq 30 \leq 35 \leq 40$	$\leq 50 \leq 100 \leq 300$
Gross density (kg/dm ³)	–	–	–	–
Bulk density (kg/m ³)	≥ 580	≥ 480	≥ 600	≥ 480
Mechanical durability (wt.-%)	≥ 97.5	–	≥ 97.5	–
Fines < 3.15 mm (wt.-%)	≤ 1	≤ 10	≤ 1	≤ 10
Binders/lubricants (wt.-%)	Nature and level are indicated.		Nature and level are indicated.	

rotation coppice, biomass residues like straw, hay, and rape press cake). Several of these materials have been tested for the production of biofuels pellets [16, 20]. Additionally the pelletizing of wheat, barley, soy extraction goat, and alfalfa for animal food applications have been tested [21, 22]. They observed fluctuating mechanical and physical properties of the produced pellets for different raw materials. Additionally, the energy demand of the pelletizing process depends on the raw material [23]. In general, it is more challenging to produce high-quality pellets out of herbaceous

biomass than out of raw materials with a high starch fraction.

Type of Compaction Most of the experiments to determine the influence of the die geometry as well as the compression force on the pelletizing process have been done with ring dies. Longer extrusion channels and smaller diameters result in a higher mechanical durability of the pellets but also cause higher energy demand. The flow rate has a linear relationship with the energy demand of the press [23]. Above a certain point,

the pellet press gets stuck and the material is carbonizes in the extrusion channel caused by too much friction and high temperatures. Generally, the densification ratio (i.e., the length to diameter ratio of the extrusion channels) needs to be higher for herbaceous biomass than for woody biomass, to achieve similar pellet qualities [13, 21, 22].

The compaction pressure in pellet mills is another important parameter influencing the pellet quality [22, 24, 25]. In general, the compaction pressure increases the bulk density of the pellets. The increased pellet durability has been traced back to the softening of lignin present in the pellet at 70°C acting as a binding agent. Consequently, pellets produced at 17 MPa and 75°C are more stable than pellets formed at 55 MPa and room temperature [26]. Thus, the effect of the compaction pressure on the pellet durability is not directly correlated and needs to be verified by further work.

Biofuels: Upgraded New Solids. Table 5 Mechanical and physical properties of different biomass pellets [16–18]

Raw material	Bulk density (kg/m ³)	Gross density (kg/dm ³)	Mechanical durability (wt.%)
Wheat straw	479–620	1.12–1.22	90.6–98.5
Rye straw	510–640	1.28–1.30	94.4–98.7
Hay	580	1.17–1.21	96.2–99.1
Miscanthus	480–649	1.11–1.33	91.1–97.5
Rape press cake	542–607	1.11–1.13	54.9–93.7

Conditioning The raw material for the pelletizing process can be conditioned by influencing the water content of the raw material, by adding binders and additives and by preheating and steam addition.

The optimum water content for the pelletizing process is different for each material. It needs to be verified and to be set by conditioning before the compaction. The optimum water content for wood pelletizing is about 12 wt.%. For herbaceous biomass, it is slightly higher. Experiments with alfalfa showed stable pellets using a raw material with 14 wt.% water content [27, 28]. Similar results have been achieved with reed canary grass where a water content of 14.9 wt.% has been optimal [29]. The water content is adjusted by adding water or steam. When steam is added to the raw material, a second positive effect is achieved; the material is preheated. The durability of blended pellets out of soy meal, ground yellow maize, and ground sorghum has been higher and the amount of fines decreased with higher temperatures at the conditioning process [6]. Additionally, the energy demand of the pelletizing process decreases with higher temperatures, but the overall energy demand of the process increased caused by the energy-intensive steam generation. For other raw materials, similar results were achieved [5, 22, 26, 29, 30].

The addition of binders (e.g., starchy residues like maize gravel, maize starch, rye flour, pea meal, lingsulfonate, or molasses) increases the stability of the pellets [22, 31–33]. Similarly, the addition of soy beans and pyrolysis oil showed positive binding effects and lowered the energy demand of the pellet mill [22]. Other additives (like lime, dolomite, kaolin, and talcum powder) are added during the pelletizing process to improve the combustion properties by

Biofuels: Upgraded New Solids. Table 6 Mechanical and physical properties of different biomass briquettes [13]

Raw material	Length (mm)	Diameter (mm)	Bulk density (kg/m ³)	Gross density (kg/dm ³)	Mechanical durability (wt.-%)
Bark briquettes	205–277	96	–	1.02–1.11	–
Wheat straw	–	15–25	440–493	0.90–0.95	95.2–99.4
Barley straw	–	15–25	318–416	0.80–0.85	97.5–99.0
Hay	–	15–25	412–438	0.95–1.10	90.2–95.0
Miscanthus	–	15	–	1.10–1.40	99.6

increasing the ash melting temperature of the pellets [34–36]. However, the addition of these substances mostly lowers the mechanical durability of the produced pellets. This can be countered by adding an additional binder [16, 35].

Milling Before pelletizing, the raw material needs to be grinded. The type of mill and the milling grade of the raw material are the most important parameters. Raw material such as wheat, barley, and soy extraction goat are grinded by using a hammer mill with a 1–4 mm sieve insert and a roller mill with a nip of 0.75 mm [21]. The grinding with a roller mill was found to be unsuitable for pelletizing. The energy consumption was lower than for the hammer mill but the mechanical durability of the produced pellets was significantly poorer. A higher reduction ratio of the raw material caused a high-energy consumption of the grinding process but a negligible higher durability and no energy saving for the pelletizing process. Similarly, more finely grounded alfalfa resulted in more stable pellets using a hammer mill with 2.0–3.2 mm sieves [22, 28]. In contrast, pellets produced with diameters of 10–25 mm from cut switchgrass and straw had better physicomechanical properties than the pellets produced out of shredded biomass (0–4 mm) [26]. On this basis, it can just be concluded that the required reduction grade needs to be tested for the respective biomass. Indeed, with increasing pellet diameter, a less fine grinding might be sufficient.

Torrefaction

Torrefaction is a mild pyrolysis process for the production of solid biofuels. It is performed at temperatures between 200°C and 300°C within an inert atmosphere. Under these conditions, lignocellulosic biomass is altered to an intermediate between wood and charcoal. After this treatment, the biomass contains typically 60–70% of the initial mass and 90% of the initial energy content referring to the lower heating value (LHV). The physicochemical properties of torrefied biomass are superior to those of the original biomass. Key benefits related to fuel storage, distribution, and utilization are:

- Energy densification
- Homogenization

- Improved grindability
- Pronounced hydrophobic character
- Enhanced reactivity

In the first half of the twentieth century, several patents established the denomination “torrefaction” for the underlying process without leading to commercial installations in that period. Not before the 1980s, growing interest in torrefied wood for applications in electrometallurgy and the domestic fuel market – namely, barbecue fuel – led to the construction of a first commercial plant in 1987 [37]. The continuous process involved chopping, drying, and roasting. Heat transfer has been realized indirectly via thermo-oil. The plant was in operation for a few years.

With the beginning of the twenty-first century, other applications renewed the interest in torrefied wood. Torrefied wood pellets have been identified as a favorable solid biofuel addressing the market of low-carbon fuels for decentralized biomass cogeneration, biomass gasification, and co-firing in coal-fired power plants [38].

Principles

Wood as well as herbaceous biomass is a complex material mainly composed of three sugar-based biopolymers: cellulose, hemicellulose, and lignin. Each of them shows a different behavior during a heating up. Therefore, it is important to distinguish between these fractions to understand the thermal decomposition of woody and herbaceous biomass.

Cellulose is the most common substance in living nature. It consists almost completely of D-glucoses forming an unbranched polysaccharide. On microscopic scale, wood cells are composed of bundles of cellulose, called microfibrils, forming a skeleton. Those bundles are coated with hemicellulose.

In contrast to cellulose, the term hemicellulose subsumes numerous distinct substances. Hemicellulose contains many different sugar monomers forming a branched polymer with an amorphous structure. Its function is manifold, reaching from reinforcing cell structure up to the provision of a reserve substance.

The third main green biomass component is lignin, a three-dimensional cross-linked aromatic biopolymer. Lignin subsumes different heterogeneous substances

that lack a defined primary structure. It acts as a binding agent for the microfibrils; it stabilizes and cements the plant structure.

The composition of hemicellulose and lignin as well as the proportion between cellulose, hemicellulose, and lignin fractions is different for every type of green biomass. Table 7 summarizes the lignocellulosic composition of different woody and herbaceous feedstocks. According to this, wood shows a higher lignin content than herbaceous biomass. Especially coniferous wood, often referred to as softwood, features a lignin content of about 30 wt.% on a dry basis.

The thermal decomposition of biomass is controlled by the chemical composition of its major components. Pyrolysis of these materials proceeds through a series of concurrent and consecutive reactions [39]. Each component reacts at different rates and by specific pathways. The rate and extent of degradation of each of these components depends mainly on temperature, particle size, and time of exposure.

Biofuels: Upgraded New Solids. Table 7 Composition of different biomass types [39–41, 43]

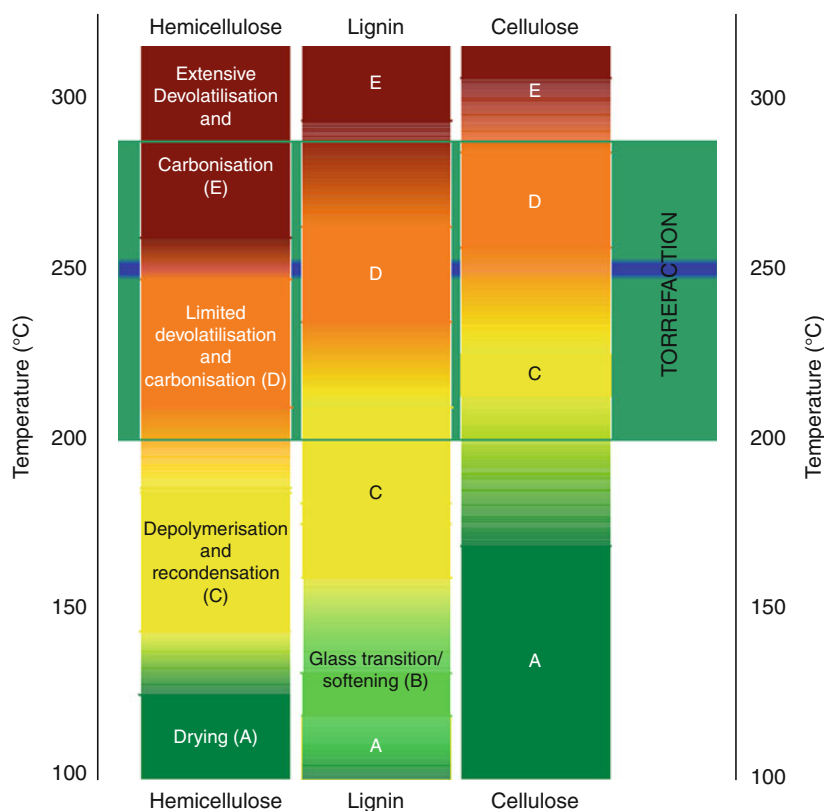
	Cellulose (wt.%)	Hemicellulose (wt.%)	Lignin (wt.%)
Woody biomass, dry basis			
Deciduous wood	40–44	15–35	18–25
Coniferous wood	40–44	20–32	25–35
Pine	42	22	30
Spruce	41	24	30
Beech	45	22	22
Willow	43	22	25
Poplar	48	18	22
Herbaceous biomass, dry basis			
Wheat straw	38	29	15
Miscanthus	43	24	19
Reed canary grass (ash free)	43	30	8
Tall fescue	25	25	14
Bagasse	38	39	20

According to Fig. 3 five temperature regimes for the pyrolytical decomposition of biomass in the low temperature range up to 300°C can be distinguished.

- Temperature regime A represents the physical drying of the biomass.
- Regime B is only valid for lignin and is defined as a temperature zone in which softening of this biomass constituent occurs.
- Regime C is characterized by depolymerization and condensation of the then shortened polymers.
- Temperature regime D leads to limited devolatilization and carbonization of the intact polymers and the solid structures formed before.
- Regime E leads to extensive devolatilization and carbonization of the polymers as well as of the solid products that were formed in regime D.

Figure 3 illustrates the different temperature regimes for each class of biopolymers. The blue line splits the torrefaction zone in a low and high temperature regime. Hemicellulose decomposition starts at lower temperatures and proceeds over a narrower temperature range as compared to cellulose and lignin. It is responsible for the main devolatilization in the torrefaction temperature regime of less than 250°C. Thereby, the reactivity of hemicellulose is depended on its specific composition. A significant difference between the decomposition of hemicellulose of coniferous and deciduous wood can be observed [42]. The latter consists predominantly of xylan-based hemicellulose, which is much more reactive and exhibits a higher degree of carbonization as compared to coniferous wood. Lignin and cellulose do not make a substantial contribution to mass loss so far, but their structure experiences chemical changes. Depolymerization reactions lead to a fragmentation and softening of the cell wall skeleton. The result is a better grindability of the torrefied biomass as compared to the raw material.

Above 250°C, both lignin and cellulose start to decompose while decomposition of hemicellulose gets extensive. A variety of permanent gases and condensable liquids is formed. The main gaseous species are carbon monoxide, carbon dioxide, water, and acetic acid. The reaction products remove part of both (i.e., the initial mass and the chemical energy represented by the organic part of the biomass). The decomposition



Biofuels: Upgraded New Solids. Figure 3

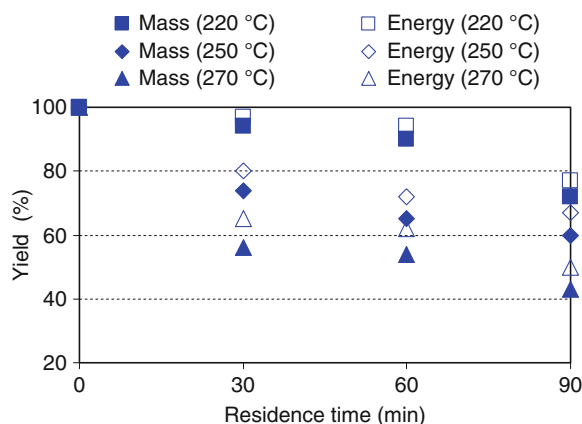
Temperature regimes for the low temperature pyrolytic decomposition of cellulose, hemicellulose and lignin (Taken from [42])

process is considerably faster at high temperatures. Decomposition is not completed within typical process residence times. Hence, higher temperatures as well as longer residence time cause lower mass yields but the remaining solids have different properties.

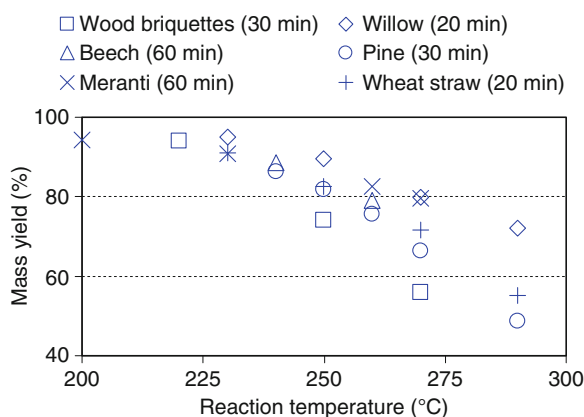
A main part of the available research work published so far concentrates on the influence of process parameters on the torrefaction of various biomass feedstocks under different conditions [1, 40, 43–48]. As the torrefaction characteristics in Fig. 4 indicate, reaction temperature and residence time are crucial for process design. Its choice faces a trade-off between: (1) high energy yields, required for good process efficiency; (2) substantial mass reduction, required for energy densification; and (3) high throughput, required for good process economics. The energy yields shown in Fig. 4 refer to the higher heating value (HHV)

of the wood briquettes, neglecting the benefits from wood drying. Even so, the energy yield of torrefaction is always higher than the mass yield. Both higher reaction temperature and longer residence times cause a more pronounced biomass decomposition. Higher temperatures lead to greater differences between energy and mass yield as compared to longer residence times. With respect to process economics, it is advantageous to adjust the reaction temperature above 250°C, allowing for residence times of less than 30 min.

Particularly, the effect of the reaction temperature has been examined since it is the most influencing parameter on process yield and product properties. Figure 5 summarizes experimental results for different types of biomass. The acceleration of mass losses for reaction temperatures above 250°C is in good agreement with the temperature regime model.



Biofuels: Upgraded New Solids. Figure 4
Mass and energy yields (HHV) from the torrefaction of wood briquettes. Values in brackets show reaction temperatures. Data taken from [44]



Biofuels: Upgraded New Solids. Figure 5
Influence of reaction temperature on the mass yield of torrefied biomass. Values in brackets show process residence times. Data taken from [1, 43–46]

Properties of Torrefied Biomass

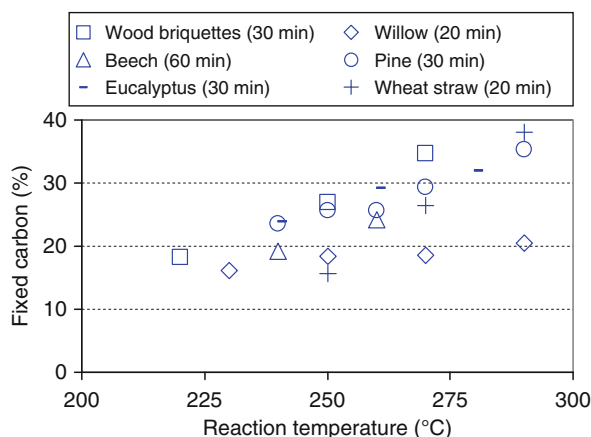
Torrefied biomass can be classified as an intermediate product between raw biomass and charcoal [44]. By adjusting temperature and process time, it is possible to make the product more or less similar to charcoal.

The net calorific value (LHV) of torrefied biomass is in the range from 18 to 22 MJ/kg for herbaceous biomass and 20–24 MJ/kg for wood. Energy density is a factor of 1.2–1.3 higher compared to the raw biomass on a dry basis. Figure 6 shows that energy densification is related to an increase of the elemental carbon fraction, accompanied by a decrease of the molecular H/C and O/C ratios (Fig. 7), which is favorable for further utilization since less water vapor is formed, improving energy efficiency.

The equilibrium moisture of torrefied biomass is around 3% (i.e., roughly three times less than the equilibrium moisture of the raw materials). Two reasons for the low water uptake are proposed: (1) tar condensation inside the pores, obstructing the passage through the solid, and (2) the nonpolar character of condensed tar on the solid, also preventing the condensation of water vapor inside the pores [44]. Hence, transportation and storage of torrefied biomass are easier as compared to the raw material.

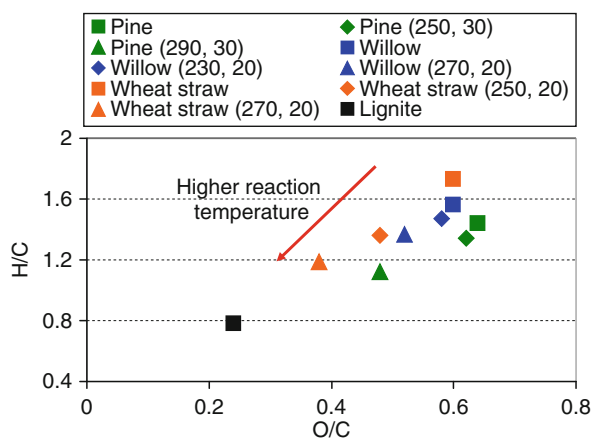
Usually, torrefied biomass is milled and pressed to form briquettes or pellets in order to enhance the handling properties. From the gasification point of view, a solid biofuel should be homogenous in chemical composition and size. Especially entrained-flow gasification asks for small particle sizes of less than 1 mm. Size reduction experiments have been performed with untreated and torrefied biomass in order to determine the power consumption of a cutting mill [40]. According to this, power consumption is greatly reduced when the biomass is torrefied. A reduction of maximal 85% has been measured (i.e., the electricity required for grinding torrefied biomass consumes only 1.5% of the biofuel energy content (assuming 40% power generation efficiency) as compared to 12–16% in case of untreated biomass). In these experiments, the mill capacity for torrefied wood was up to 6.5 times the capacity of untreated wood. Additionally, particle size distribution and shape is more uniform for torrefied wood.

The improvements of the grinding properties are caused equally by physical and chemical changes [40]. The chemical changes responsible for this behavior occur relatively fast and in the first stages of decomposition (temperature regimes C and D in Fig. 3). Hence, reaction temperatures above 250°C and residence times of >10 min hardly will bring further improvements.



Biofuels: Upgraded New Solids. Figure 6

Fixed carbon of torrefied biomass. Values in brackets show process residence times. Data taken from [43–46, 49]



Biofuels: Upgraded New Solids. Figure 7

Van-Krevelen diagram of raw biomass, torrefied biomass and coal. Values in brackets show residence time and reaction temperature. Biomass data is taken from [43, 45], coal data from [50]

Torrefaction Plants

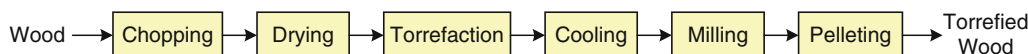
Torrefaction plants integrate several mechanical and thermal processes (i.e., chopping, drying, torrefaction, cooling, milling, and compaction). If the process aims to produce a commodity fuel as shown in Fig. 8. Compaction usually means pelletizing of the torrefied biomass since this kind of packing provides the best storage and transportation properties.

The first commercial-scale torrefaction plant was built in the frame of an EC Demonstration project in 1987 in France [37]. The plant has been operated with forestry wood. The capacity has been 12,000 t of torrefied wood per year. The product was mainly used as a coke substitute in electrometallurgy and some was sold as barbecue fuel. The plant has been decommissioned in the early 1990s for economic reasons [42].

This so-called Pechiney process [37] was based on an indirectly heated screw reactor. The process consisted of three main sections: chopping, drying, and torrefaction. Figure 9 gives an overview of the different basic process units and their interconnection.

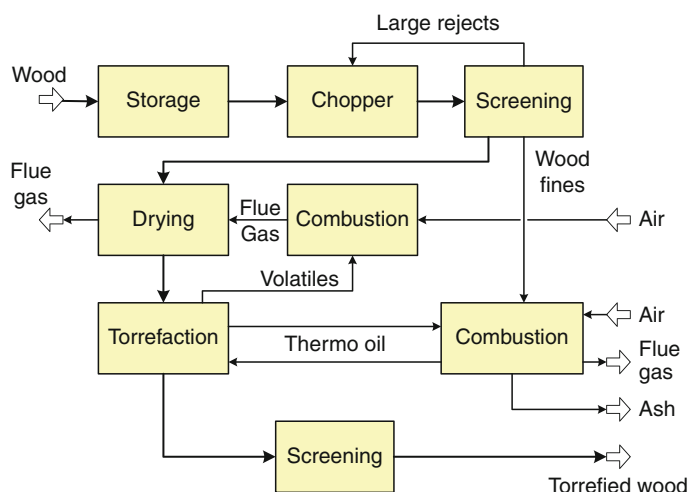
Forestral wood with typically 40% moisture content was first chopped and screened. The wood fines were burned to supply heat to thermo oil circulating between the torrefaction reactor and the boiler. The remaining wood chips were dried to 10% moisture content before being fed into the torrefaction reactor. Hot air from the combustion of the torrefaction gas was used for this purpose.

The reactor was developed as a post-dryer for solids requiring homogeneous product moisture content. The size of that kind of reactor is typically determined by the heat duty, as the area for heat exchange is limiting. Higher feed moisture contents lower the reactor throughput capacity. Temperature control of the reactor is easy because of the limited heat transfer rates that are responsible for a limited capacity and long residence times of more than an hour. The result is a comparatively expensive process



Biofuels: Upgraded New Solids. Figure 8

Process steps of a torrefaction plant



Biofuels: Upgraded New Solids. Figure 9

Flow sheet of the Pechiney torrefaction plant in France according to [42]

with production costs of roughly 100 €/t without feedstock costs [42].

The energy efficiency is in a range of 65–75% including feedstock and utility usage. Serious energy losses occur due to fines production during cutting and sieving of the biomass feedstock [42].

With the beginning of the twenty-first century other applications renewed the interest in torrefied wood. Worldwide, different companies announced plans for the construction of torrefaction plants on an industrial scale of some 10,000 t/a. They address the market of low-carbon fuels for decentralized cogeneration and co-firing in coal combustion and gasification plants. Most of the plants should not mainly supply a single recipient but produce a marketable biofuel suitable for different industrial applications.

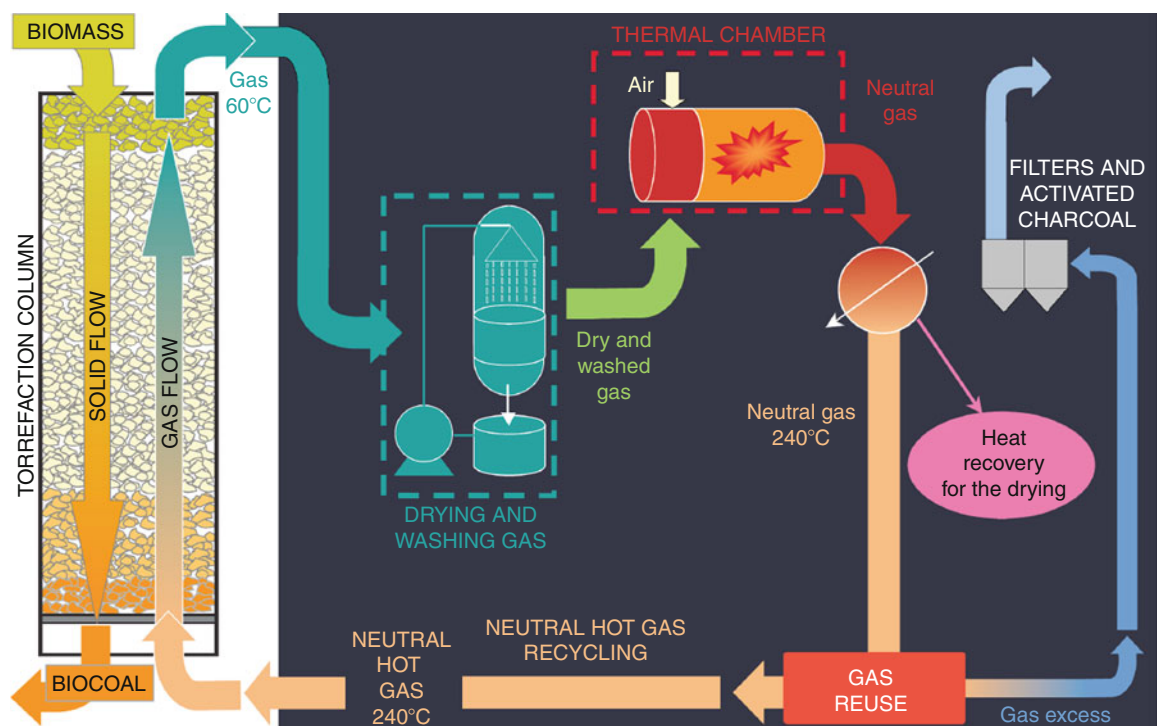
Recently announced torrefaction plants rely on direct heat transfer. Most of the suppliers utilize rotating drums or circular trays which origin from drying technology. Others operate with a moving or fluid bed (Fig. 10). Direct heat transfer is usually realized by conducting the hot flue gas from the combustion of the torrefaction gases through the reactor, but some concepts operate with circulating inert gas reheated by heat exchanger. In that case, heat is generated by burning the torrefaction gases and some additional wood fuel.

Hydrothermal Carbonization

Although the scientific investigation of hydrothermal transformation of biomass is ongoing for decades, efforts of technical applications are quite young. Therefore a brief historic overview of hydrothermal carbonization is given.

In 1913, Bergius described the hydrothermal transformation of biomass into a coal-like product as one result of his investigations of the natural coal genesis [51]. In the 1920s and 1930s this investigations were continued and extended. These results have been confirmed in new test series in the 1960s. Around 1995 various companies started with the development of a process for the use of waste biomass (like sewage sludge) and for decontamination and disinfection. Based on this, the SlurryCarb™-process was developed as the first ever commercial process for the hydrothermal production of a coal-like product out of organic waste. Several laboratory and demonstration plants have been built and tested since 1997. In 2008, a first commercial pilot-plant started operation in Rialto, USA. It converts 900 t of biomass per day.

Besides solid biomass with limited water content usually converted thermochemically, there is a certain potential of wet biomass available (like manure, food industry wastes, digestates from biogas processes,



Biofuels: Upgraded New Solids. Figure 10

Torrefaction process using a moving bed reactor (Source: Thermya)

sewage sludge, and black liquor) [52]. The necessary drying obstructs the use of these kinds of feedstock in classical thermochemical processes. In case of wet biomass with 20–30% dry organic matter, the heat generated by the combustion of the organics has the same amount as the heat needed for the vaporization of the water. Therefore, wet biomass should be converted in processes without a need for preliminarily drying.

Mainly two processes fulfill this requirement for wet biomasses: biogas production and hydrothermal conversion. In the biogas process, wet biomass is biochemically converted into a methane-rich gas. However, mainly carbon hydrates are usable and the lignin remains unconverted due to biological constraints. This means, that the energy of the lignin cannot be used. Additionally, there are organic materials like straw, which can hardly be solubilized in the biogas process. In contrast, hydrothermal processes are able to convert all organic fractions.

Common hydrothermal processes are hydrothermal carbonization (HTC), hydrothermal gasification, and hydrothermal liquefaction also known as hydrothermal

upgrading (HTU) [53–57]. Since the main product is a solid, only hydrothermal carbonization is tackled within the following explanations.

Principles

The properties of water at enhanced temperature and pressure may vary from those of cold water [57–59]. Above the critical point – characterized by 375°C and 221 bar – water is able to dissolve silicon dioxide and fat. At these conditions, basic properties of water change (e.g., the dielectric coefficient, the ion product) [60, 61].

During hydrothermal carbonization, the organic material is preheated. Due to this thermal energy, the macromolecules in the biomass are degraded and smaller molecules are formed out of them [62]. The pH-value mainly influences what kind of compounds is degraded. While carbohydrates can be decomposed under sour conditions, lignin degradation asks for a high pH-value. Favorably it will be converted into phenols while aldehydes and furfurals will be produced

from the decomposition of cellulose and hemicellulose [63–65]. Starting with these smaller molecules, new larger compounds are built. In these reactions, water is eliminated. Reaction mechanisms of hydrolysis, dehydration, decarboxylation, aromatization, and condensation polymerization are involved in the conversion of biomass into biocoal [66].

The new substances formed after the partial degradation of the macromolecules have properties like humic substance or lignite. For energy applications, the target has a lignite-like quality. In contrast to pyrolysis coke, which in principal consists of carbon, the product of the hydrothermal carbonization (so-called biocoal) is characterized by the elemental formula C_6H_2O .

Hydrothermal carbonization covers two different processes, the classical hydrothermal carbonization and the SlurryCarb™-process. The former uses mild reaction conditions of 170–250°C and 10–20 bar. A catalyst (e.g., citric acid, ferric sulfate) is necessary. Catalysts allowing to lower reaction temperature or residence time are a major target of fundamental research. At present, the operating conditions have to be applied for 3.5–16 h. This very long residence time is a weak point of the entire process.

The SlurryCarb™-process operates at 220–270°C and up to 220 bar. It needs only 10–60 min for the carbonization [67, 68]. However, high-pressure reactors are required. Additionally, above a reaction temperature of 240°C the phenol load of the wastewater increases strongly [69].

Energy Balance The hydrothermal carbonization is an exothermal process. Therewith, the process may proceed without an external heat supply. But the energy converted from chemical energy into heat is not contained as usable chemical energy in the product any more. This heat generation can amount of up to 30% of the energy contained originally within the feedstock. Thus, the energetic efficiency of the conversion process of biomass into biocoal is between 70% and 90% [67, 70].

For the operation of the hydrothermal carbonization, it is necessary that the biomass particles are surrounded by water. Otherwise, the reactions cannot occur regularly. Usually, HTC reactors require a pumpable or pasty feedstock. The minimum water content for such properties differs depending on the

other characteristics of the biomass. Typically, a water-to-dry-matter ratio of 2:1 is necessary. In that case, one-half of the generated heat is needed for preheating the feedstock. Furthermore, the biocoal and the water do not separate themselves. After a mechanical water separation by filtering or centrifugation, an additional thermal drying is necessary to provide an energy carrier from the biocoal. For the efficiency of mechanical separation, first results are available [71]. As a result, after 2.5–5 min in action, water content in biocoal of 30–45% is reached. With centrifugation after SlurryCarb™-process, 50% water in the product is achievable [68].

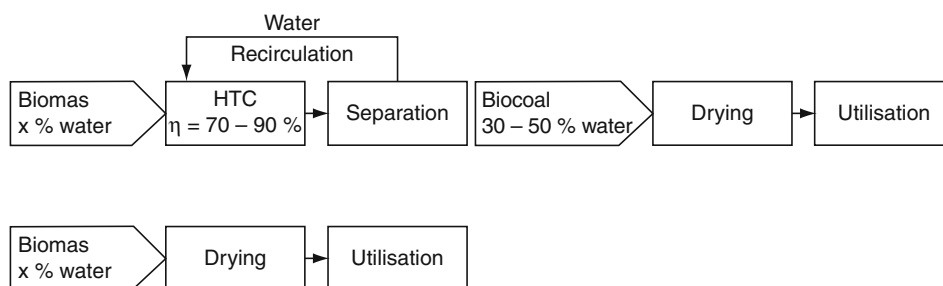
Of course, the heat for feedstock preheating and drying is partially regenerable. But, considering the technical possibilities of heat transfer, characterized by the necessary temperature differences and the heat losses, hardly any heat for external use will remain.

All over, the energetic efficiency of the hydrothermal carbonization depends on the water-content of the raw material and how easy it can be dewatered mechanically.

Figure 11 compares brief process chains of biomass utilization, for example, combustion with and without hydrothermal carbonization.

Waste Water Until now, several questions of the hydrothermal carbonization are not clarified comprehensively. One of the most important open questions is the wastewater treatment. Different types of water pollutants have been identified (i.e., inorganic as well as organic substances). The water-soluble inorganic substances available in the feedstock will be dissolved. This affects both, the minerals typical for biomass (like ash components, nutrients) and the inorganic feedstock pollutants (like heavy metals). In this case, water pollution corresponds with a decontamination of the solid phase. The leaching of ash components can upgrade the combustion behavior.

Organic substances in wastewater can have two sources. The first source is water-soluble organic compounds preliminarily available in the feedstock. Those of these compounds not degradable under the conditions of hydrothermal carbonization could be dissolved in the process water. Additionally, substances formed in the hydrolysis process and not consumed during the new forming of large compounds can remain in process water. Typically, different kinds of



Biofuels: Upgraded New Solids. Figure 11

Process chains for the utilization of biomass with and without hydrothermal carbonization

Biofuels: Upgraded New Solids. Table 8 HTC waste water ingredients [71]

Parameter	Value
pH-value	3.7–7.2
Biochemical oxygen demand (BOD)	10,000–42,000 mg/L
Chemical oxygen demand (COD)	24,200–68,500 mg/L
Total organic carbon (TOC)	9,000–36,100 mg/L
Nitrate-nitrogen	2.9–58 mg/L
Ammonia-nitrogen	3.4–4.1 mg/L
Phosphate- phosphor	0.2–47 mg/L

phenol-like substances can be found in the wastewater. The chemical oxygen demand is correspondingly high. Typical amounts of wastewater ingredients are listed in Table 8.

Phthalates, pyrazines, phenols, other oxygen containing cyclic compounds, and aliphatic and aromatic hydrocarbons mainly represent the content of organic substances [71].

Apart from wastewater recycling, different water purification processes are possible. The content of organic pollutants, represented by chemical oxygen demand (COD), can be decreased by 90% within a biogas plant (i.e., anaerobic treatment). Downstream, a final cleaning can be done with activated carbon [71]. Often discussed is integration with a biogas plant in a manner that the HTC plant uses the digestates and the biogas plant uses wastewater from the HTC.

The flue gas of the HTC process contains less than 5% methane and more than 90% carbon dioxide with low amounts of hydrogen, oxygen, and hydrogen sulfide [72].

Hydrothermal Carbonization Processes

Currently, the transformation from laboratory scale to technical plants is ongoing. Therefore, the state of technology outlined below might change rapidly.

The reaction temperature and pressure of the hydrothermal carbonization are easy to handle with available process technology. The core question of the commercialization of the HTC process is the residence time. For example, for a resistant time of 12 h and a fuel output (dry matter) of 10 MW a reactor volume of 50–100 m³ will be necessary to the discussed feedstock water contents. For the use of mechanical dewatered sewage sludge with the typical water content [73], the necessary reactor size for about 35 bar can increase up to 250 m³. This is why the reduction of resistant time is crucial for the successful technical implementation. The SlurryCarb™-process with decreased residence times of minimum 10 min [74] is in this case is advantageous. But, because of the described problems with the wastewater quality, the resistant time reduction must be reached by advanced catalysts for the future.

The long residence time causes the use of several reactor types. Tube reactors and discontinuous reactors allow for the control of the residence time. Because of the necessary size of the reactors, uncommon designs (like sub-terrestrial pressure vessels) are discussed.

The SlurryCarb™-process is the only process realized in a larger pilot plant. This plant converts 900 t of

sewage sludge a day to 170 t of solid fuel [68]. For every other process, the construction of a demo plant or pilot plant is ongoing.

Biocoal Properties

The properties of biocoal depend on the reaction conditions. With increasing residence time, the product changes its manner from humus like to lignite like. Analysis values are listed in Table 9. General combustion properties are given in Table 10.

These chemical analysis values, especially the heating values and the contents of carbon, hydrogen, oxygen, nitrogen, and sulfur, show that biocoal can be used in energetic applications.

The biocoal is described to be a lignite substitute. Many chemical properties are in fact quite similar to lignite. But, it has to be seriously observed, that at least one of the main combustion properties, the content of volatile matter, differs completely. This parameter of HTC-biocoal is rather in a range typical for green

biomasses. Because the ignitability and the properties of the flame are substantially determined by the content of volatile matter, the combustion of HTC-biocoal cannot be similar to lignite combustion. Instead of that, the combustion behavior will be between green biomass and lignite. Future research has to show which kind of combustion technology, either lignite technology or biomass technology, is able to utilize HTC-biocoal most efficiently.

The solid product has a macroscopic particulate shape or the shape of the feedstock particles remains. Only the physical and chemical properties change and the particles get a fissured and porous structure. Thus, the fibrous structure of the green biomass is destroyed. The biocoal is a highly functionalized carbonaceous material [77] microscopic composed of agglomerates of microspheres. This means that the biocoal is neither in the chemical surface properties nor in the microstructure, similar to pyrolysis coal with little functional groups at surface and also with a porous structure characterized by lots of micro-channels.

Biofuels: Upgraded New Solids. Table 9 Elementary analysis and heating value of biocoals from HTC compared with its biomass feedstock (dry matter) [75]

Feedstock	Condition	Elementary analysis					Heating value (LHV) (MJ/kg)
		C (%)	H (%)	N (%)	S (%)	Ash (%)	
bark mulch	green	45.5	6.1	0.6		5.8	18.7
	HTC-biocoal	55.7	5.8	0.6		6.8	22.1
leaves	green	45.3	6.8	1.1	0.02	11.1	18.1
	HTC-biocoal	56.4	6.1	1.1	0.01	11.7	24.2

Biofuels: Upgraded New Solids. Table 10 Combustion properties of biocoal from HTC compared with brown coal and biomass (dry matter) [1, 76]

	HTC-biocoal	Brown coal (Rhineland)	Brown coal (Lusatia)	Softwood (spruce)	Straw (wheat)
Water content (%)	8	11	10.5	15–20	10–20
Ash content (%)	1.5	4	6	0.6	5.7
Volatile matter (%)	74.5	46	45.5	82.9	77.0
Sulfur content (%)	0.2	0.4	0.8	0.02	0.08
Heating value (LHV) (MJ/kg)	20	22.2	21	18.8	17.2
Ash softening temperature (°C)	≈1,200	>1,100	>1,200	>1,400	<1,000

Other crucial properties for the applicability of the biocoal are the water content and in connection with this the consistency. Depending on the water content of the feedstock, the biocoal occurs as a suspension. Because of this, the water cannot be removed only with mechanical processes up to a content which make utilization in a classical thermochemical process (like combustion or gasification) possible. That is why an energetic reasonable application of the hydrothermal carbonization requires also an answer to the question of water removal.

In the contrary, the products of hydrothermal gasification and hydrothermal upgrading can be extracted from water by phase separation processes, which cause hardly any energy demand.

Biocoal Applications

The use of biocoal in lignite application processes is one option. Because of the analogy of some of the fuel properties, biocoal may substitute lignite in different fields of use. Such a substitution saves greenhouse gas emissions, which is important for the climate protection and governmentally funded in many countries.

Because the content of volatile matter of HTC-biocoal is similar to biomass and its heating value is high in comparison with biomass, pellets from biocoal (or with a percentage of biocoal) might be an important addition for the pellet markets of the future. Uses for coal sludge are currently in a research stage. They can avoid the energy demand for drying. Gasification and combustion of coal-slurries are state of the art, but in this case the energy demand is only removed into the gasifier or furnace.

In general, the solid fuel produced by hydrothermal carbonization requires a complex conversion process for solid fuels. In most cases, gaseous or liquid products will be easier to apply.

Apart from the energetic application, the use of biocoal from HTC for the fertilization of soil and carbon sequestration is intensively discussed. Here, biocoal is mixed into topsoil. But, the advantages (e.g., increase of fertility and stability of the carbon disposal) to be achieved in practice are currently not clarified [78].

Biocoal has hardly any analogy with activated carbon or carbon black. That is why biocoal cannot

be expected to be a substitution for these. Nevertheless, there are serious activities for the production of engineering carbon materials via hydrothermal carbonization [79].

Summary and Future Directions

Each of the discussed processes provides an important possibility for the production of high value solid biofuels. The main process characteristics are:

- Pelletizing and briquetting are physical processes; torrefaction and hydrothermal carbonization also influence the chemical structure and the chemical behavior of the fuel.
- Pelletizing, briquetting, and torrefaction occur in a gaseous atmosphere while hydrothermal carbonization runs in hot pressurized water
- Pelletizing, briquetting, and torrefaction require dry feedstock; hydrothermal carbonization has the greatest advantages for wet biomass.

Because of the different process characteristics, these processes have their own specific future directions and potential impacts on the development of certain areas of science.

For the further development of solid biofuels, produced by pelletizing and briquetting, the compaction process needs to be understood in depth to adjust the process parameters in an optimal way. Therefore, the interactions of the parameters influencing the process and their influence on the resulting properties of the compacts have to be figured out. Important questions are, for example, the influence of particle size distribution and the water content of the raw material on the mechanical durability of the compact or the optimal compaction pressure needed for a certain compact strength and the possibilities to influence it by conditioning or by adding binding agents. Besides the adjustment of optimal compact properties, the knowledge of these correlations allows the optimization of the process itself and of the energy efficiency which directly affects the costs of the biofuel production. Therewith the goal is the simulation of these processes for better understanding and for an optimal compaction of the raw materials.

The benefits of pelletizing and briquetting processes are (1) a higher durability because of reduced water

content and (2) a higher volumetric energy density. Furthermore, admixtures compensate variations. Nevertheless, there is no substantial change in the chemical composition during the pelletizing and briquetting processes [18, 80, 81, 83].

Torrefaction process technologies have reached a commercial scale. The process technologies are derived from drying technology. The major drawback is a comparatively long residence time of some 10 min resulting in large reactors with high investment costs. Process economics and the development of a sufficient market for torrefied biomass pellets is still an open question, but recent investment decisions indicate good market opportunities.

The torrefaction product is a highly reactive solid biofuel with good combustion properties. Torrefied biomass pellets are suitable for biomass combustion and gasification plants as well as for co-combustion and co-gasification plants.

The main question for the future of hydrothermal carbonization is for which feedstock and for which process chains an energetic, economic, and environmental benefit can be reached. Therefore, a lot of balancing and assessment work has to be done. Open questions in addition are: (a) decreasing of residence time and (b) equipment optimization for biocoal production (i.e., water recycling, removal of inorganic pollutants, search for high toxic organic components, removal for wastewater treatment, and combustion, as well as pelletizing behavior for energetic use).

In general, the possibility of thermochemical use of wet biomass is an important chance. But, the question not answered until today is whether hydrothermal carbonization is the best alternative compared with other hydrothermal processes and the biogas process. According to the fuel characteristics and the economic conditions, each of the three described technologies could find its special use for energy production in the future.

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Biogas for Electricity Generation, Hi-tech Applications

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Article Outline

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Glossary

Biogas Biogas is a gas which is produced as waste product during anaerobic microbiological breakdown of organic substances. The main constituents are methane and carbon dioxide.

Biogas cleaning Biogas cleaning is a technical process which adapts the biogas quality to a defined gas quality defined by the subsequent usage. That includes mainly the reduction of trace gases (H₂S, NH₃, water vapor, and others). Biogas cleaning does not focus on the removal of carbon dioxide from the biogas.

CHP unit Combined Heat and Power unit which consists of a gas-burning engine driving a generator which produces electricity. The waste heat from electricity production can be used for further applications.

Landfill gas Landfill gas is a special type of biogas which is produced in landfills during the degradation of the organic constituents of wastes. It is characterized by many organic long-chain trace gases.

Sewage sludge gas Sewage sludge gas is a special type of biogas produced within wastewater treatment plants during the anaerobic treatment of sewage sludge. It is characterized by the content of siloxanes.

Definition of the Subject

This entry focuses on the development, its reasons, and the perspectives of the electricity supply based on biogas through anaerobic digestion. This sector is worldwide very important for decentralized energy supply from organic materials. Beneath this fact, electricity from biogas reduces the demand for fossil fuels and reduces greenhouse gas emissions connected with fossil-energy supply systems. Thus the development of this sector is analyzed. Based on this, the possibilities and the challenges of electricity supply from biogas and its contribution to reach national and international renewable electricity targets is discussed.

Introduction

Biogas can be produced from a very broad variety of organic substrates. Internationally, the main biomass sources are wastewater treatment sludge (to produce sewage sludge gas) and organic wastes from agriculture (e.g., excrements from animal farming, residues from processing of agricultural products). Additionally, high importance has to be paid to landfill gas production and utilization. In some countries as, e.g., Austria and Germany, the use of energy crops contributes additionally significantly to biogas production [10, 11].

Due to the fact that all these different kinds of biogases consist of roughly 50–70% of methane, the gas can be used easily as a fuel. In the past, very different engines have been developed to produce electricity from cleaned biogas. Parallel to these technologies, biogas can be used for cooking purposes, for heating, as well as a fuel for vehicles. But the latter is not a topic of this article.

History

The history of biogas production is already very long – especially for small-scale applications. Some very old experiences are recorded already from China and Persia. In industrial large scale, the first biogas plants were constructed for the purpose of wastewater cleaning. About 1897, at a hospital in Bombay, India, the first plant was constructed where the gas was used for lightening the streets, and from 1907 for the operation of a motor to run an electricity generator. After this beginning, more and more anaerobic wastewater treatment plants mainly in Europe were constructed and equipped partly with generators [1].

Due to the relatively high costs of electricity production from biogas, the gas was mainly used for heating and lightening, as well as a fuel for transportation purpose. But also, some enthusiastic farmers started between 1980 and 1990 with the construction of digesters and electricity generators with electrical capacities mainly below 20 kW based mainly on animal excrements. The electricity was produced to cover the own electricity demand within their farm.

With the implementation of feed-in laws for electricity into the national electricity grid, the technology

got incentives, and a continuous growth of the use as well as the plant size began [2].

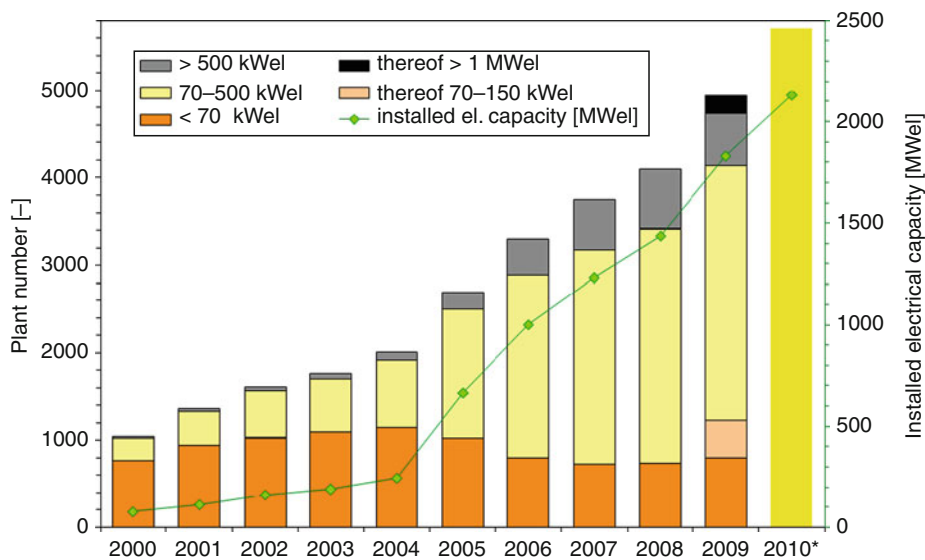
For example in Germany, based on the incentives introduced in 1999, the electricity production from biogas increased rapidly. Especially financial incentives for the production of electricity from energy crops–based biogas lead to the very strong development (Fig. 1) especially in this area.

Within Europe, about 3,000 MW electrical capacities based on biogas (including landfill gas and sewage sludge) have been installed in 2007. Only Germany contributes with about 50% to this number [4]. Compared to the international situation, Europe dominates the electricity production from biogas [5].

Looking into the future, it is estimated, for example, for Germany that in the year 2050 a total capacity of electricity production from biogas of about 11,000 MW can be reached. Worldwide, the capacity in 2050 is estimated to reach about 100,000 GW [5]. Thus a very rapid growth of this sector is expected worldwide.

Technology

After some cleaning processes, biogas shows very good combustion properties. This is also true for the use in



Biogas for Electricity Generation, Hi-tech Applications. Figure 1

Development of electricity production from biogas (without landfill gas and sewage sludge gas) exemplarily for Germany [3]

engines. For that reason the use of biogas for electricity supply has a long tradition. Thus, there are lots of experiences available and the obstacles for electricity supply from biogas under very different conditions are very well known. This is analyzed within the following chapters.

Biogas Production

Biogas is produced mainly from organic residues and wastes. Such organic matter can result from animal breeding (excrements), crop production (harvest residues), processing of agricultural products (residues from beer brewing, vegetables processing, beverage industry, and others), organic municipal or industrial wastes, organics in wastewater streams, wastewater cleaning processes, and many other sources. Energy crops are another (costly) biomass resource for biogas production which are actually only used in some countries. The question if a biomass source can be used for biogas production is answered by its anaerobic degradability.

Biogas production is a microbiological process taking place under anaerobic conditions (at total exclusion of oxygen). The microorganisms involved into this process are omnipresent but concentrated in anaerobic sources as, for example, the stomach of ruminants. For applications with the aim of biogas production, the ruminant's stomach has more or less to be emulated so that the process is mainly carried out in so-called fermenters which are gastight and mainly equipped with some stirring devices. Very simple household digesters which supply cooking gas, e.g., for families in rural areas of developing countries as well as industrial-scale solid substrate digesters (garage-type), are constructed without stirring devices. They show often comparably low gas yields. Therefore, most industrial applications realize some movement within the fermenter (Fig. 2).

The choice of the fermenter type depends mainly on the substrates. But also, the economic-frame conditions as well as the chosen installation company have a considerable influence. Therefore, a broad variety of technologies can be found on the market.

The dimension of the fermenter depends on the amount of biomass to be treated and the biological dimensioning to avoid an overload of the microbiological

community. It also plays an important role if a one-staged or more-staged process is realized. So far, single fermenters with dimensions between 20 and 8,000 m³ can be found on the market. Typical fermenters used, e.g., in Germany, for agricultural biogas plants are sized between 1,000 and 2,500 m³. Biogas amounts of 2.5–500 m³/h are produced which are equivalent with about 5–1,000 kW electrical capacity of a gas engine. For larger plants (the largest known is 10,000 m³/h biogas production at one single place), two or more fermenters are connected or placed parallel.

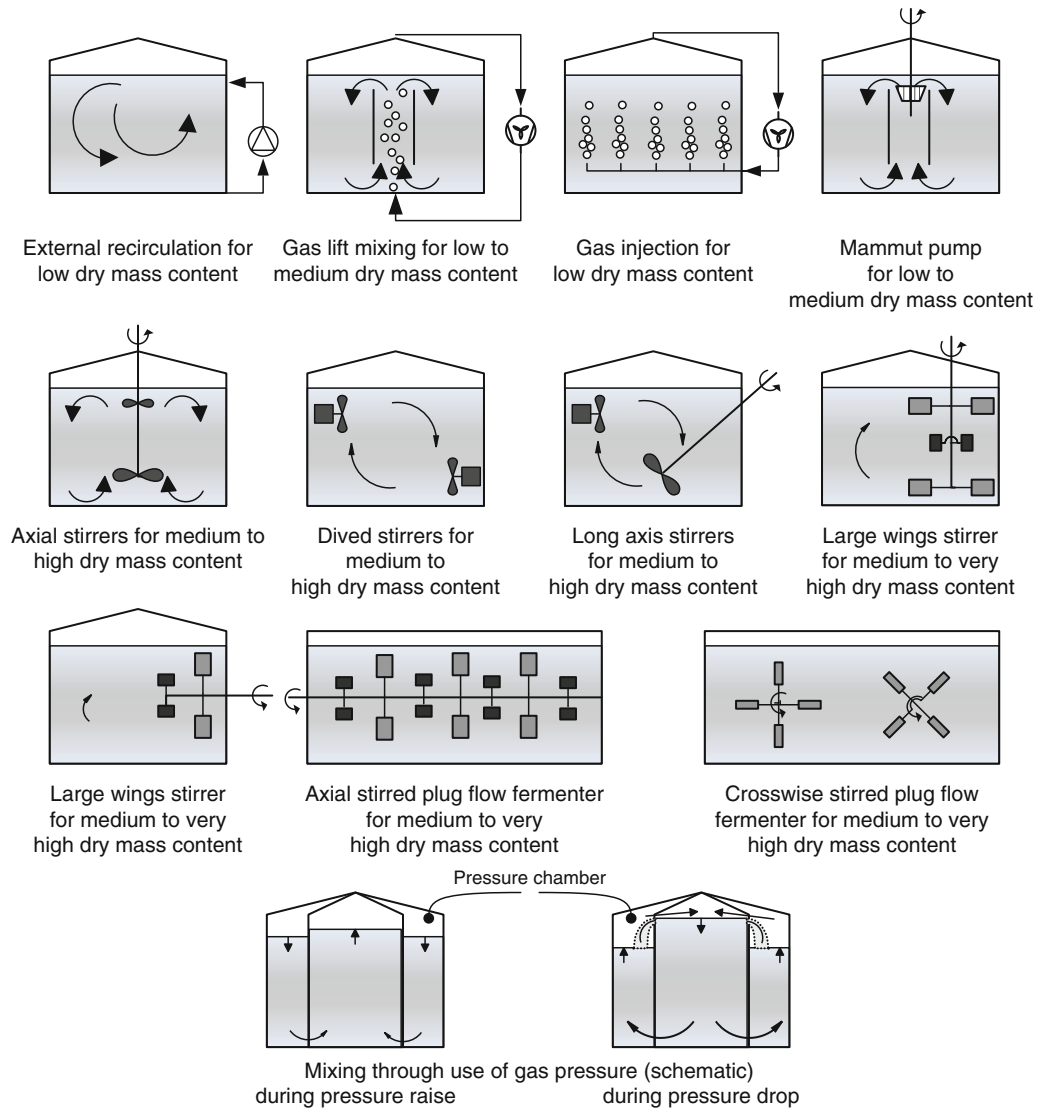
Much attention has to be paid on the right temperature for the fermentation process. Active bacteria do not tolerate fast changes in temperature resulting in a reduced efficiency and in lower degradation rates within the fermenter. Thus, the temperature in the fermenter should be constant and changes should not exceed 2 K/week. For this reason, heating systems in industrial scale fermenters should be designed carefully.

Internal fermenter heating systems can be designed in various ways. One option is that stainless steel heat pipes are installed within the fermenter some centimeters away from the fermenter walls. Another possibility is that they are embedded within the concrete walls and the concrete bottom. The heat exchange rates are much higher when the pipes are not installed within the concrete, but the heat exchanger rate may be reduced due to dirt attachments at the pipes fixed within the fermenter. Additionally, technical stirrer faults can cause demolition of the pipes. Heat pipes at the fermenter bottom cannot be suggested because almost all biogas plants show sedimentation of material within the fermenter, reducing the heat exchange significantly.

External heating in heat exchangers is realized in cases where a continuous circulation of the fermenter content is technically necessary. If this is not the case, external heating requires additional electrical energy for a circulation pump. The advantage is that only external heating allows a regular cleaning of the heat exchanger surface.

All fermenters – except the garage-type fermenters – require movement of the substrate through any type of pipe.

Substrates with very high content of solids (20% and more) can be transported in screw conveyors.



Biogas for Electricity Generation, Hi-tech Applications. Figure 2
Overview on the main types of industrial fermenters with stirring [6]

Due to high abrasion, screws and walls have to be constructed very robust preferably from stainless steel. Very positive effects on continuous operation and low maintenance show applications of walls which can be removed easily in two parts and which can be adjusted depending on the abrasion of the screw (the diameter will slightly decrease). Stones and solid parts have to be removed from the substrates before passing screw surveyors.

Substrates with a lower content of solids are transported in pipes mainly. They are moved by

pumps. Special requirements on the pumps result from substrates with 5–20% solids content. In these cases, best experiences are reported from the use of rotating piston pumps and eccentric screw pumps, which can be found on almost every agricultural and industrial biogas plant nowadays. They are used for substrate supply to the fermenter as well as for transportation purposes between different fermenters and storage tanks. Only the removal of the digested slurry is not realized by a pump mostly. It is realized with an open siphon where the overflow from the fermenter

leaves due to gravity and due to processes of new substrates supply into the fermenter without additional energy demand. For this reason the fermenter will not be overfilled and maintain a constant filling level.

Operational experiences for the fermentation unit of a biogas plant are in most cases very good. Special attention has to be paid on the quality of the stirrers, the additional technical equipment, and the internal coating of the fermenters. The aggressive atmosphere within the fermenter (due to the formation of sulfuric acid) requires stainless steel or totally coated surfaces of steel and concrete, especially in the gas room under the roof of the fermenter. Fermenters are estimated with a technical lifetime of 20 years and more when they are constructed at high quality. But the technical equipment shows in most cases only technical lifetime of maximum 10 years [7].

Fermenters are able to produce biogas all year round. Practical experiences show that it has to be expected that due to biological or technical problems, the fermenter has to be opened about each 3 years. For example, a removal of a sand layer, the exchange of the stirring system, or some maintenance work has to be done. Then it has to be calculated that the fermenter is out of operation for 1–4 four weeks, and thereafter a new start of the plant is necessary which leads to a startup phase with a reduced biogas production rate. Annually (without a real opening of the fermenter), a fermenter is available with roughly 95%. Due to biological process problems, it is possible that 5% of the year in average, not enough biogas can be produced to run the CHP plant at full load.

Electricity Production from Biogas

So far basically only motor-CHP units are used for electricity production. Additionally to a minor extent micro-gas turbines (worldwide probably about 100) are used. Almost independent on the device, the biogas has to be cleaned from H_2S , water vapor, and – dependent on the substrate – siloxanes.

H_2S , which can form sulfuric acid and increase corrosion effects, must be removed to levels between 150 and 400 ppm depending on the requirements of the supplier of the CHP unit. It is always suggested to go for a very low H_2S level in the gas to minimize maintenance work at the CHP unit and to prolong the

intervals for oil exchange; for example, levels of 100 ppm and below would result in notable reductions of maintenance cost which in many cases result finally in improved economic behavior of the overall biogas plant [7].

In many cases, with a low H_2S content, it could be sufficient to use the so-called internal biological sulfur-removal method. Here the H_2S content is reduced with sulfur-reducing bacteria (sulfobacter oxidants) living in the gas space of a fermenter. They convert H_2S into elementary sulfur which is then removed with the digested substrate. Such a sulfur-removal requires on the one hand sufficient area for settling of the bacteria (e.g., a layer of wood beams or nets) and, on the other hand, the continuous supply of some oxygen (about 3% to maximum 6% compared with the biogas production rate [8]).

For a higher H_2S content and/or improved reduction rates, additional equipment for external biological, physical, or chemical desulfurization is required. This can be [9]:

- External biological desulfurization, where within a washing column, a biological desulfurization as described above takes place under controlled conditions
- Biochemical washing, where the H_2S is bound in a first column chemically to, e.g., soda lye and is separated from that in a second column without bringing oxygen into the gas system
- Sulfide precipitation in the fermenter, where sulfide binding chemicals (Fe-III-chloride, Fe-II-chloride or Fe-II-sulfate) are given with the substrates into the fermenter
- Adsorption to activated charcoal, where in separate vessels, the raw gas is led through a packing of charcoal which allows the highest degree of gas cleaning

For water-vapor reduction in the gas phase, at least a condensation of water in the raw gas-pipe system has to be realized through piping the gas under the earth. For improved drying of the raw gas, the application of technical dryers is suggested. They have to be resistant against formation of sulfuric acid in the condensate. It has to be noted that the gas will be saturated with water at the temperature of fermentation, and notable condensate amounts have to be handled.

Siloxanes are relevant mainly for gases resulting from digestion of sewage sludge and municipal solid waste as well as from landfill gas. They can cause depositions of silicates in the engine. They could be the reason for massive technical problems. For reduction mainly, activated char coal filters can be used.

The different CHP-unit types do show differences in their technical performance and operational behavior. Mainly, it has to be distinguished between gas-otto-engine-driven CHP units, ignition-oil CHP units, and micro-gas turbines which are in practical and commercial use [9].

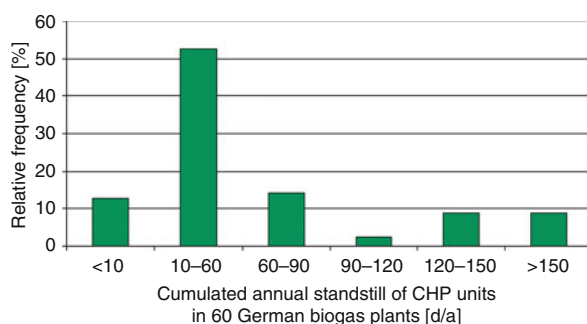
- Gas-otto-engines only use the biogas as fuel. They are operated with the otto-engine principle with air in excess and equipped with a turbocharger. The methane content in the biogas has to be above 45% (Table 1).
- Ignition-oil engines use the biogas, but always between 7% and 10% additional ignition oil (diesel, vegetable oil, biodiesel). The engines use the same principle as conventional diesel engines and are operated with air excess. In dependency of the gas quality and availability, the ignition oil share can be increased up to 100% so that not necessarily the engine has to be turned off during maintenance work at the biogas plant (Table 1).

- Micro-gas turbines only use biogas as fuel. They are fast-running gas turbines with a small electrical capacity (today max. 600 kW) with air preheating within a recuperator and a generator driven by the expanded gas after its combustion. The methane concentration in the fuel has to be above 35%, and the turbines tolerate higher H₂S concentrations than other CHP units. The high frequent noises can be quietened easily, and the waste heat can be delivered at a much higher level than from the other CHP units (Table 1).

From practical applications, it was measured that most plants do not run nonstop throughout the year due to maintenance but also due to faults and problems at the plant. For regular maintenance, about 150–200 h/year (less than 10 days) have to be calculated. Keeping that in mind and on condition that the fermenters continuously produce the full gas amount for full load of the CHP unit, it can be expected that the availability of the whole plant would be at 97%. Practically, gas production cannot run at exact 100% of the demand and should not waste gas what cannot be used in the CHP unit. Thus the gas production is mostly at about 95% or less in average compared with the capacity of the CHP unit. Therefore – as shown in Fig. 3 – in practice, most plants show a calculated standstill time

Biogas for Electricity Generation, Hi-tech Applications. Table 1 Comparison of the different types of CHP units; according to [7]

Parameter	Gas-otto engines	Ignition-oil engines	Micro-gas turbines
Capacities electrical	300 kW...3 MW	5 kW...500 kW	10 kW...600 kW
Electrical efficiency	35...43%	35...42%	21...33%
Thermal efficiency	40...44%	40...44%	50...60%
Heat-level water cooling/thermal oil	95/105 °C (50%)	95/105 °C (50%)	Overheated steam
Heat-level waste gas	300–400 °C	300–400 °C	300–600 °C (100%)
Lifetime	60,000 h	35,000 h	40,000 h
Emissions	NO _x and CO medium level	NO _x and CO at borders of legal limits	Very low
Special remarks	Engines designed for gas/biogas use	Highest electrical efficiency at low capacities; use of adapted standard diesel engines	Low noises



Biogas for Electricity Generation, Hi-tech Applications.

Figure 3

Theoretical cumulated standstill time of CHP units in practical agricultural biogas plants; the frequency is calculated as the share of really produced electrical energy of theoretically possible electrical energy production [7]

less than 60 days. The plants with longer standstill times in Fig. 3 had during the period of analysis notable biological problems, they were not full time in operation or they had any technical fault so that they should be excluded from evaluation.

Expected Developments

Starting from the state of the art described above and keeping in mind the strong research and development activities ongoing currently on an international level, it is expected that during the next 20 years, substantial improvements will be done.

Biogas production is a biotechnological process. But research activities just start with modern biotechnological methods. Therefore, within the years to come, new knowledge about the microbiological processes will be available which will lead to technical improvements so that it is expected that around 10% increase in the biogas yields could be realized. Additionally, the biogas plants will be better adapted to the substrates as well as the microbiological requirements. Also complicated or challenging substrates (like grass or straw) can be used in a more efficient way.

Regarding the electricity production process, it is expected that electrical efficiencies will slightly raise with about 2% in common CHP units. Fuel cells can find their way from demonstration activities into practice, what leads to significant higher electrical efficiencies

(45–60%). Other technologies are not expected to improve the overall behavior of decentralized electricity generation from biogas.

The overall plant behavior will show increased efficiencies in terms of reduced own heat and electricity demand, increased availabilities due to better knowledge on the processes, more applied measurement technologies, as well as more reliable technologies. Thus the expected full load hours are expected to rise to about 3–5%. At the same time, higher requirements regarding environmental impacts of biogas technology will lead to reduced direct and indirect emissions from today between 1% and 5% of the methane produced to a value lower than 1%.

Obstacles

There is no technology without obstacles. Technically it can be stated that biogas technology is well known, and biogas plants can be constructed and operated satisfactorily when suitable substrates are used. Obstacles result more from economic view interfering with the organizational/legal framework.

Thus the main question is the applicability of the electricity produced. For an economic successful operation, it is very important that the framework allows trading of heat and electricity to neighbors and feed in into national energy grids. Without these prerequisites, a biogas plant has to be designed for decentralized energy supply for a single company and then a balance between energy supply and energy demand has to be reached.

The second important question is if electricity production from biogas is economically viable. The production costs are often higher than local energy costs. This depends mainly on the costs for substrates and revenues for the products. The latter includes not only energy but also solid or liquid residues (i.e., digested slurry) which are a valuable fertilizer. Effects of reduction of greenhouse gas emissions and other environmental advantages should also be taken into account. Regarding the revenues for the electricity in many countries, very good experiences were gained with defined long-lasting guaranteed tariffs for each kWh fed in into an electricity grid.

Economics of Electricity from Biogas

The costs for electricity production from biogas depend on very many factors, mainly connected with substrate supply. Therefore only few examples are given from the German market of industrial biogas applications. Thus Table 2 shows the main cost positions for three different typical plant sizes and types.

Generally, the production costs of electricity from biogas are higher than 0.1 €/kWh, and so far higher than electricity production costs from fossil fuels in most cases (i.e., grid connected electricity generation in large-scale units). Only plant C shows lower costs, but this is caused by the very promising situation that the substrates are not connected with costs. If for some of the substrates paying would be necessary (and this is the case, e.g., for organic waste streams from food processing competing with fodder for animal

breeding), the production cost would rise above 0.1 €/kWh. This would also be the case for plant A when the vegetable residues would have been paid.

Thus there is the question if some further revenues could reduce the production costs. This could be the case if heat could be supplied and sold for a typical price between 0.02 and 0.035 €/kWh_{th}. Additionally, it could be the case that a farmer who uses the fertilizer can be convinced about the worth of the organic fertilizer and pays something for it. Last but not least, it is possible to generate revenues from acceptance of residues and wastes (e.g., from slaughterhouses), where the producer of the waste has to pay for to get rid of the waste material. But all in all, it is to assume that the influence of these revenues will never be more important than maximum 0.03 €/kWh_{el} production-cost reduction.

Biogas for Electricity Generation, Hi-tech Applications. Table 2 Typical cost assumptions for different typical German biogas plants

Parameter	Unit	Plant A	Plant B	Plant C
Capacity electrical	kWel	190	600	1,200
Electrical efficiency	%	38%	39%	40%
Substrates used	–	50% Manure, 20% grass, 30% vegetable residues	35% Manure, 65% energy crops	20% manure, 30% food production wastes, 30% slaughterhouse wastes, 20% used fats
Full load hours	h/a	7,500	7,700	7,700
Electricity production	kWh _{el} /a	1,425,000	4,620,000	9,240,000
Heat production	kWh _{el} /a	1,650,000	5,212,308	10,164,000
Specific investment costs	€/kW _{el}	4,500	3,500	3,000
Capital costs	€/a	98,325	241,500	414,000
Substrate costs	€/a	30,000	270,000	0
Maintenance costs	€/a	25,650	63,000	108,000
Operational costs	€/a	60,625	152,060	272,120
Residues transportation and use costs	€/a	18,000	36,000	60,000
Total annual costs	€/a	232,600	762,560	854,120
Specific electricity production costs	€/kWh _{el}	0,163	0,165	0,092

Thus for making the biogas production and use for electricity generation economically viable from an investors' point of view, financial incentives are necessary. This is especially true if energy crops – offering the largest potential today – shall be used.

Future Directions

Today, electricity from biogas has in many countries settled as a promising renewable electricity supply technology.

Thus it is expected that worldwide the biogas production as well as the electricity production from biogas will continue to grow in the future. Considering the significant expectable improvements in overall efficiency and environmental behavior of biogas plants, the technology seems one of the most promising among the possibilities of sustainable energy supply.

In the future, with increasing fossil-fuel prices and optimized technologies for biogas production and use, the production costs will converge at the level of fossil-energy prices. So in 10 or 20 years, electricity from biogas might be able to compete at the market commercially.

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Biogas Production and Energy Crops

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Glossary

Soil texture Describes the composition of the soil with regard to the proportion of the different grain size fractions of the mineral constituents. By adhesion forces in the varying pore sizes, the soil texture determines to a large extent the water storage capacity of soils as well as the capillary rise of water from deeper soil levels.

Effective root zone Soil depth, from which annual field crops can take up water by their rooting system. It is determined by soil texture as well as weather conditions.

Evapotranspiration coefficient (TC/ETC) The TC is a measure for the amount of water transpired by a plant stand for the production of a unit of plant matter (liters per kg DM), that is the reciprocal value of the water use efficiency (WUE). In addition to the transpiration, the water release of a plant stand is largely determined by the evaporation of the soil. Both processes are subsumed under the term “evapotranspiration,” which can then accordingly be described by the evapotranspiration coefficient (ETC).

Field capacity The field capacity describes the amount of water in the pores of a water-saturated soil that can be held against gravity after a period of more than 3 days.

Vernalization Induction of stem elongation/development of main shoot and generative phase by the impact of cold temperatures. Vernalization need of plants, e.g., winter cereals, prevents their blooming before winter.

Water use efficiency (WUE) Measure for the amount of plant matter produced for a unit of water transpired. It is equal to the reciprocal value of the transpiration coefficient.

Crop rotation Temporal succession of crops on one site.

Second crop Crop that is grown after a winter intercrop.

Intercrop Crop grown between the cropping of two main crops. Differentiations can be made between summer intercrops (main mass production before winter) and winter intercrops (main mass production after winter dormancy).

DM/oDM – (organic) dry matter Dry matter refers to the harvested biomass after exclusion of the water, which is part of the fresh matter. For a specification of biogas yields, organic dry matter is given as a reference value, which makes a subtraction of inorganic ash fractions from dry matter values necessary.

Mycotoxin Toxins formed by mold fungi, which are toxic to humans and animals. Most important

mycotoxins in wheat are deoxynivalenol (DON) and zearalenon (ZEA).

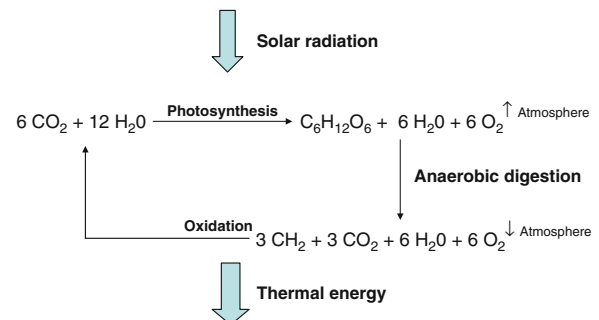
WC – Whole crop Crops are referred to as whole crops, when harvested before full ripeness as entire subsurface plant material mainly for silage preparation.

Definition of the Subject

Conversion processes in anaerobic digestion are realized by anaerobic prokaryotes that have been playing a major role in the transformation of chemical structures for a long period in evolution history. The product of such an anaerobic digestion process is a substance mixture. Its gaseous phase consists largely of methane and carbon dioxide and can be used for energetic purposes (Fig. 1).

The multitude of bacteria which are active within this anaerobic degradation process have the ability to digest a large spectrum of non-lignified biomass. Besides residual and waste biomass, the cropping of biomass (i.e., energy crops) is a possibility to supply larger amounts of biomass for anaerobic digestion processes.

Indisputable from a sustainability viewpoint is the fact that the land area for the production of agricultural goods is limited and that a conversion of land of high value for the storage of carbon or to sustain biodiversity should not take place. For this reason, the existing agricultural area should be used as efficient and



Biogas Production and Energy Crops. Figure 1 Schematic energy conversion process exemplarily demonstrated by the example of glucose without taking conversion losses into account

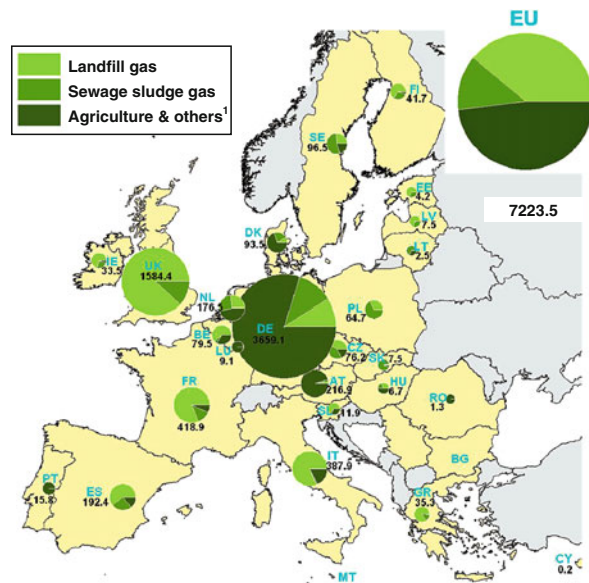
sustainable as possible also for energy provision. The cropping of energy plants can therefore be regarded as an important piece of a puzzle to complement existing production systems with its specific characteristics.

The agricultural production of substrates, which are the raw material for a sustainable substitution of fossil fuel energy, aims at designing systems that make a most efficient conversion of solar energy and a maximized substitution of fossil fuels possible. At the same time, all potentials should be utilized to ensure a long-term sustainability. Therefore, an intensive production and an environmentally sound production are to be harmonized. This article is going to concentrate on findings from Central Europe.

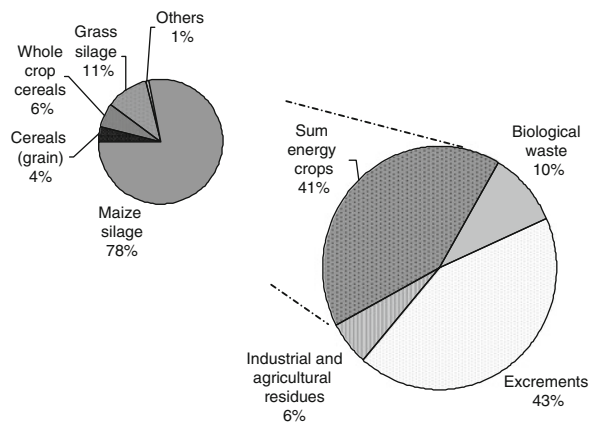
Introduction

Throughout the world, national legislations have introduced systems to promote an increased usage of biomass for energy production. Currently, in some countries incentive systems, which guaranteed fixed prices for electricity generated from renewable resources (feed-in-tariffs), are supporting this political goal [1, 2]. For example, by the amendment of the German Renewable Energy Act (Erneuerbare-Energien-Gesetz, EEG) in 2009, the German government put in place favorable conditions for biogas production. Tariffs set by this law guarantee degressive reimbursement for electricity from biogas for a period of 20 years. In addition to the basic reimbursement for each kWh dependent on capacity classes, additional premiums can be accessed. One of these premiums is a bonus payment for electricity from renewable raw material, which amounts to 0.07 €/kWh for plant sizes of up to 500 kW [3]. Similar incentives can also be found in other countries throughout Europe.

As shown in Fig. 2, the production of biogas from agricultural substrates contributes already noticeable to the overall Biogas production in Europe. The substrates currently used, for example, in Germany are dominated by animal excreta if the agricultural substrates are analyzed according to mass or volume. From an energy-related point of view, dedicated energy crops, which are again dominated by maize silage, make up the largest single share in Germany (Fig. 3).



Biogas Production and Energy Crops. Figure 2 Primary energy production from Biogas in Europe in 2007 in kilotons of oil equivalent [ktOE] (Data from [4]). ¹“Others” are the communal digestion of solid waste as well as the centralized CHP-usage of biogas fed into the grid



Biogas Production and Energy Crops. Figure 3 Substrate input in German biogas plants 2008/2009 – percentages of total fresh matter (left) (Adapted according to data from [5]) The shading is roughly indicating the energy yield of each substrate

The provision of energy crops is directly competing with food and fodder production. These two sectors are experiencing an advancing rate of specialization on a very narrow spectrum of crops in cultivation and

in a reduction in the number of crop types being rotated. The development of energy cropping as a new branch of production is therefore connected with the hope of providing possibilities for diversification in the context of a multifunctional agriculture [6]. High land productivity, maximum energy gain involving cost effectiveness and the optimization of non-commodities of cropping systems embedded in existing production regimes are major objectives of focus in public research.

Production and Provision of Energy Crops for Biogas Production

Biological and Agricultural Basis

The efficiency of the yield formation of agricultural crops is determined by an interaction of growth factors, that is, factors that are necessary for the metabolic processes of plants. These include solar radiation, temperature (progression), soil characteristics, and water availability as well as a controllable supply of macro- and micronutrients. For the choice of suitable crops and the design of cropping systems, the knowledge of these interactions is essential. The influence of the specificity of growth factors on yield can be roughly depicted by yield functions.

Efficiency of Photosynthesis The production of energy crops is, just as the entire plant production, based on the photosynthetic activity of higher plants. Ensuring a high efficiency of transforming solar radiation to simple organic carbon compounds, which are available for the formation of complex substances of content, is therefore a precondition for high energy yields.

The chain reaction involves the storage of solar radiation in energy-rich phosphate compounds. These are utilized to incorporate CO_2 into the acceptor molecule Ribulose-1,5-bisphosphate (RuBP) by means of the activity of the enzyme Ribulose-1,5-bisphosphate carboxylase oxygenase (RubisCO). As can be derived from the name, the enzyme also acts as an oxygenase. Hence, energy losses in the process of energy fixation are experienced. This part of the respiratory processes, which depends on the relation of O_2 -to- CO_2 partial pressure, is called photorespiration.

Some plant species, which due to their differing physiology are called C_4 plants, possess an intra-leaf

mechanism that enables them to retain CO_2 in their mesophyll cells. As this can result in CO_2 concentrations of up to 20 times as high as in most plants, C_4 plants have major advantages in efficiency. The fact that sufficient CO_2 is available for metabolic processes results in a minimized loss from photorespiration. Furthermore, with an increased photosynthetic activity, plants can respond to high light intensities, whereas insufficient concentrations of light are the limiting factor for most C_3 plants in solar radiation of more than 250 W/m^2 . This explains why only C_3 plants can profit from an increase in CO_2 concentrations in the atmosphere (Fig. 5).

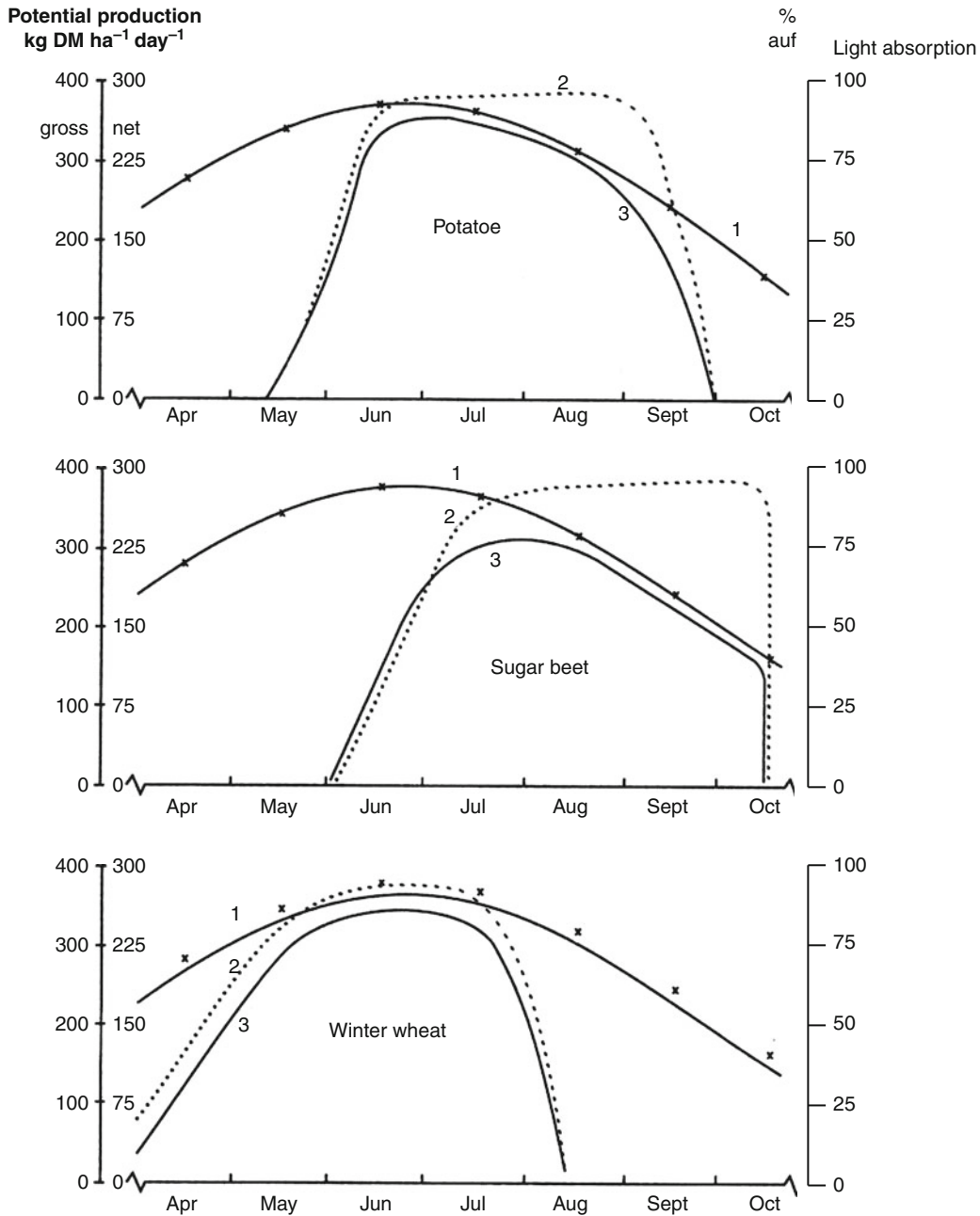
The efficiency of photosynthetic processes is theoretically determined by the amount of primarily generated carbohydrates in relation to the radiation provided. According to the basic processes of photosynthesis, theoretical values of more than 30% for assimilation in the chloroplasts can be calculated. In fact, efficiency values are limited by some inevitable losses.

Only a part of the solar radiation in the spectral range of 400–720 nm can be absorbed by pigments in the membranes of the chloroplasts. In relation to the overall radiation, this bandwidth covers only about half of the total energy reaching the earth's surface. Losses from absorption by photosynthetically inactive structures and from transmission and remission amount to at least 9%. Roughly, 8.5% of the primordial radiation is lost during absorption by pigments as thermal energy. This can be explained by the fact that the energy of the different photons within the bandwidth exceeds the energy needed for driving the separation of charges. The transportation of electrons and the secondary processes of carbon assimilation require 19–22%. Processes of photorespiration and dark respiration use another 6.2–7.3% in C_3 -plants; dark respiration in C_4 -plants accounts for 4.9–5.8% of the losses relating to primordial energy. The differences in these ranges confirm the advantage of C_4 -plants in terms of efficiency. In a nutshell, different authors published an overall maximum efficiency level of 5.1% (C_3) and 6% (C_4) in chemically fixed energy in relation to the available radiation energy [7–14].

Efficiency levels that can be practically achieved are significantly lower. Maximum levels that could be measured in field experiments may reach a level of about 3.8% [15].

From the agronomists' point of view, it is vital that growing conditions are designed to allow for an approximation to the photosynthetically set limits of growth during the vegetation period. Harvesting and

the reestablishment of a sufficient leaf-area index in the successive crop limit the time span for an optimized utilization of the progression of solar radiation in temperate climates (Fig. 4).



Biogas Production and Energy Crops. Figure 4

Potential of plant production derived from the radiation levels available (1); percentage of available radiation used by the crop stand (2); and calculation of daily increment (3) for potatoes, sugar beet, and winter wheat ([16] according to [17])

Temperature and Water Usage All processes determining plant growth are influenced by temperature. Depending on the species, a temperature range supplying optimum conditions for growth can be defined. C_4 -plants show higher optimum levels (above 30°C) than C_3 -plants (around 20°C). This can be explained by the relatively lower affinity of RubisCO for CO_2 . Additionally, in warm conditions, CO_2 has a relatively lower solubility level in comparison to O_2 . However, if temperatures are too low, the higher energy exertion for the refixation and transport of CO_2 by C_4 -plants can be observed; this explains why the efficiency advantage of these plants can only be realized under conditions of adequate temperatures (Fig. 5).

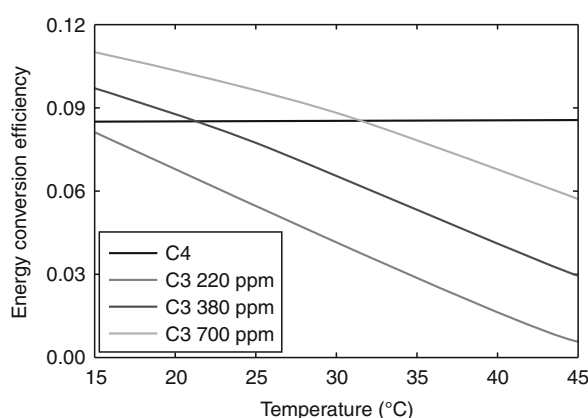
Furthermore, temperature has an essential influence on the water balance of crop stands. This balance is decisively determined by the transpiration of leaf surfaces and the uptake of water by the roots. Due to the temperature-dependent differences in water potential between the atmosphere and the soil, water can move through the plant transporting nutrients and perform its essential functions in all the metabolic processes of the plant.

Of utmost importance is the evaporation through the stomata, by which gas is exchanged with the surrounding. The opening of the stomata is regulated,

which accounts for the fact that water and gas exchange processes of plants are directly related to each other. This also explains why the available amount of water during the vegetative span, as well as the efficiency of its usage is crucial for crop yield and security.

During the growth period, values for the evapotranspiration coefficient (ETC) of about $350 \text{ l H}_2\text{O/kg DM}$ for winter wheat, about $250 \text{ l H}_2\text{O/kg DM}$ for winter rape and approximately $200 \text{ l H}_2\text{O/kg DM}$ for maize could be identified. Due to different growth periods, ETCs of winter-annual crops are higher than those of summer-annual crops. By nature, low temperatures and low radiation intensities limit the growth of winter crops during long periods, so in relation to the available water, only little growth can take place. Hence, water consumption during the main growth periods should be regarded. In fully developed and healthy maize stands, this ranges roughly between 3.7 and 4.3 mm/day. Due to the described intra-leaf mechanism of CO_2 -refixation, maize, just like other C_4 -plants, exhibits higher water use efficiency (WUE). Still, necessary amounts of water cannot be provided by precipitation, which in the largest part of central Europe averages only between 1.6–2.5 mm/day. Therefore, with an increased optimization of other growth factors, also in temperate regions, water increasingly becomes the central limiting factor for plant yields.

In addition to the spatiotemporal distribution of precipitation, the soil functions of retention and storage of water from times in which water cannot be used for main growth periods is becoming increasingly important. Field capacity as well as the depth in which plants can potentially take up water by their roots is strongly determined by soil texture. In dry years, the effective root zone can vary between 50 (coarse sand) and 110 cm (loamy silt). By combining values of field capacities and effective root zone, the maximum amount of stored water available for plant growth varies between 30 and 220 l/m^3 . From this quantity of water in combination with the amount of precipitation water added and the water use efficiency of plants, limits for the potential yield of crop stands under the given conditions can be estimated.



Biogas Production and Energy Crops. Figure 5 Theoretical energy conversion efficiencies of photosynthesis of C_3 - and C_4 -plants as a function of temperature and CO_2 -concentrations of the surrounding environments [14]

Soil and Nutrient Supply Soil development is based on the processes of physical and chemical weathering and the successive translocation of surface rock substratum. Besides minerals of varying size and composition, air, water, and organic mass are part of the layer called the pedosphere. The organic mass contains dead biomass as well as living organisms that are involved in matter-transforming processes.

Plants depend on absorbing all mineral nutrients (oxygen and carbon excluded) and trace elements from the soil. Therefore, physical and chemical properties of soils are essential for the attainment of yield potentials. Besides the thickness of the top soil layers, soil texture plays an important role. By structuring adhesion forces in the differently large pores, soil texture significantly determines the water storage capacity of soils (see above) and the capillary rise of water from deeper levels.

Products from the weathering and transformation of matter also determine the ability of soils to store nutrients. The enormous surface area of minerals, which are part of the clay fraction, can fix ions that are dissolved in water (e.g., nutrient salts) in the process of adsorption. This protects them from being eluted; due to the reversibility of the process, they are still available for plants.

Other than the composition of mineral constituents of the soil, organic matter, which is supplied to soils and subsequently underlying constant de-, trans-, and reformation processes, is relevant for storage functions. Input matter for dead organic material, called humus, is mainly made up of harvest residues, green manure, and organic fertilizers such as fermentation residues from biogas plants. The enormous plurality of forms in which organic matter in soils exists can be structured by its stability with regard to decomposition processes. Non-humic substances like polysaccharides, amino acids, and P-compounds show little resistance to decomposition. In the course of decomposition, plant nutrients such as nitrogen (N), sulfur (S), and phosphorus (P) compounds as well as potassium (K), sodium (Na), magnesium (Mg), and calcium (Ca) salts are released.

Parts of the organic matter, intensively altered with regard to morphology, show stabilization against

further decomposition processes. These so-called humic substances form a large reservoir of nutrients due to their large exchange capacity. Furthermore, humic substances can occlude particulate organic matter within their structure and form compounds with clay minerals. This, in addition to its positive influence of transformation and storage functions, leads to a friable soil structure and the so-called mellowness of the soil [18].

For maintaining central soil functions and a constant flow of nutrients, a steady recirculation of organic substances is necessary. Since most forms of energy cropping aim at maximizing the energetic utilization of aboveground biomass, conflicts of interests can arise (see section [Humus Balance](#)).

From the perspective of plant production, planning the recirculation of residues is part of plant nutrition strategies. Central tasks in this planning are therefore to optimize the nutrition supply for the plants as well as to sustain and improve soil functions. The basic principle is that nutrients withdrawn from the soil should be returned. According to current knowledge, at least 14 elements are necessary for the normal development of plants. Quantities needed vary between the development stages, though.

The strongest influence on yield is to be seen in the variation of nitrogen supply. The reason can be found in the fact that nitrogen (N) is largely relevant to mass development and that its prevalence in most soils, relative to other nutrients, is yield-limiting. The uptake from soils mostly happens in the form of Nitrate (NO_3^-) or Ammonium (NH_4^+) ions. Besides organic fertilizers, the fixation of atmospheric elementary nitrogen in the course of cultivating legumes as well as the atmospheric deposition (caused, for example, by nitrogen emissions from combustion processes), the most important nitrogen source is mineral fertilizer. In contrast to nitrogen drawn from processes of the decomposition of organic matter, mineral fertilizer allows for a more pinpoint application.

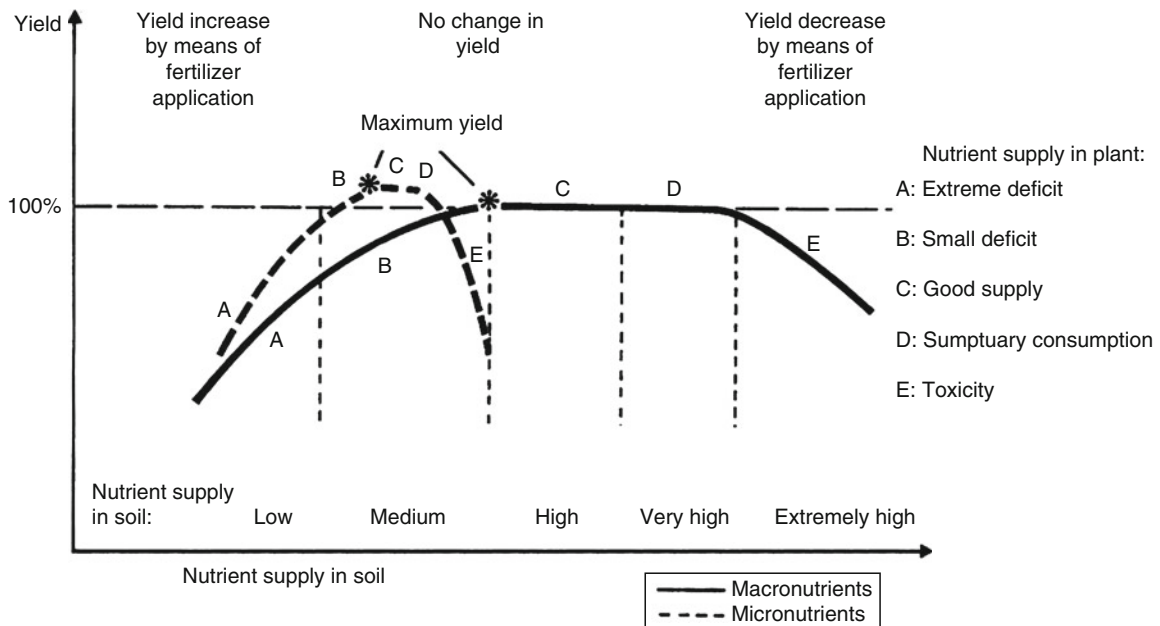
Apart from nitrogen, fertilizer application of phosphorus (P) and calcium (Ca), as well as, depending on geological origin of the soil, of potassium (K) and Magnesium (Mg) has to be undertaken regularly. Phosphorus (P) is taken up by plants mainly in an

inorganic form (H_2PO_4^- und HPO_4^{2-}). It has a key function in energy-related processes and is a component of organic compounds that are crucial for a plant's life. Potassium, Magnesium, and calcium are taken up as cations (K^+ , Mg^{++} , and Ca^{++}) from the soil. Potassium is used for osmoregulation and influences numerous enzymatic reactions, which are important for the formation of macromolecules. Transportation of assimilates, winter hardiness, and drought resistance are raised by a good supply with potassium. Likewise, Magnesium is a nutrient for constructional and functional purposes. It is used in oxidation processes of the chlorophyll during radiation impact and is employed in energy-related metabolism as well as for the activation of enzymes. Calcium is an important component of the plants' matrix structure but also accounts for the bulking state of plants and the activation of various enzymes. The application of calcium is mostly aimed at regulating pH-levels for the optimization of nutrient availability for plant nutrition. Furthermore it stabilizes soil texture due to its bond-building function, which prevents puddling, erosion, and oxygen shortage. Other nutrients

are available in sufficient quantities in most central European agricultural soils.

The amount of nitrogen fertilizer given should be oriented at the withdrawal of the plant stand. One of the central challenges is to plan optimum quantities before knowing the realizable yield. From an economic point of view, the optimum amount is characterized by the fact that the cost of the last unit of nitrogen given should be covered by the net revenue of the additionally attained amount of yield (marginal revenue). By approaching and exceeding the maximum attainable yield, the latter decreases (Fig. 6).

An optimized application of fertilizer, which avoids sumptuary consumption, can contribute to minimizing negative effects on the environment. Such negative effects are, for example, the leaching of nutrients into deeper soil layers, groundwater or receiving streams, nitrous gas emissions or the loss of nutrients into ecosystems by means of erosion processes. Risks of nitrate leaching are particularly high. Therefore, within Europe various regulations exist regarding fertilizer application.



Biogas Production and Energy Crops. Figure 6

Relation between nutrient supply in the soil and in the plant respectively and the yield [19]

Organic Substance Groups as Raw Material for Anaerobic Digestion

The different substances incorporated in plant matter show, depending on their specific composition, a differentiated suitability for decomposition in anaerobic processes. Therefore, they can contribute in a differentiated manner to biogas and methane formation respectively which means, that the composition of plant matter plays a decisive role for the usability of chemical energy fixed in the substrate.

Organic Substance Groups The primary substances formed in the process of photosynthesis and the higher-molecular carbohydrates, lipids, and proteins formed in the following metabolic processes serve for the formation of the matter of plant cells, which are largely composed of macromolecules. The structure of these macromolecules follows universal laws; largely, they are formed according to the principle of replication from smaller units that are similar or congeneric.

For an assessment of the transformation of differently composed material, long-term experiences in the field of ruminant nutrition can be referred to. The analysis of plant material and its description can be conducted by the *Weende Analysis Standard* and its extension by van Soest [20]. This standard does not produce exactly defined chemical substances as parts of the cell wall or cell interior, but it can deliver statements on the energy value and the usability for digestion processes.

Internal Cell Substances In the field of ruminant nutrition, those parts of the cell substance that are soluble in a neutral detergent are called internal cell substances. A further subdivision can be done by classifying the different substances as part of different nonstructural carbohydrates, crude protein, crude fat, crude ash, or as part of the residual fraction.

Crude ash is the inorganic part of the assay, which remains after incineration. Still, the minerals remaining are mostly not isolated constituents of plant matter but are mostly part of organic compounds. Crude protein includes the actual protein fractions as well as the nonprotein nitrogen compounds. Being the nitrogen-consisting fraction, crude protein is being calculated from the nitrogen

content of the assay and the average nitrogen content of proteins.

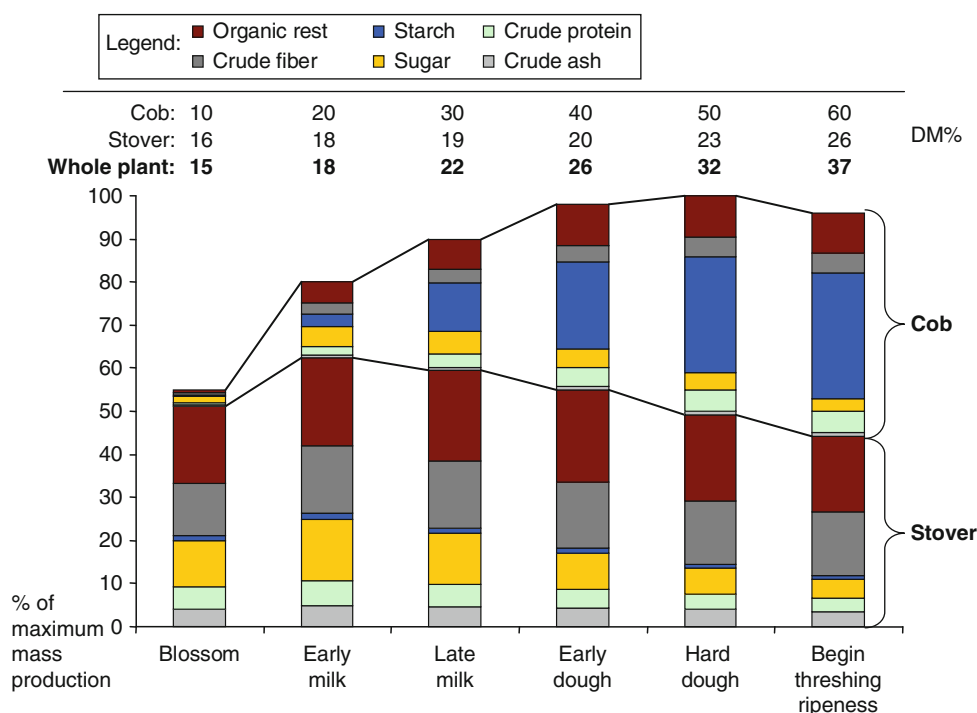
All substances that can be extracted using ether are called crude fat. Apart from actual fats (Triglycerides), this fraction also includes fat-like substances (lipoids). Nonstructural carbohydrates can be subdivided into water-soluble carbohydrates; that is, sugars and fructanes that consist of a buildup of laevulose components as well as starch, which functions as the most important reserve carbohydrate build up of sugar components. All other substances soluble in a neutral detergent are called organic residues and mostly consist of organic acids.

Cell Wall Substances (Skeletal Substance) Those parts of plant matter that are not soluble in a neutral detergent are called cell wall substances or NDF (neutral detergent fiber). A further subdivision can be made by classifying the different substances as part of the fraction of structural carbohydrates (pectins, hemicelluloses, and cellulose) or lignin.

Cellulose forms the skeletal substance of the non-lignified cell walls and is relevant for the tensile strength of the plant. The buildup is formed by the connection of monosaccharides (D-Glucose) by hydrogen bonds. The collective term hemicellulose includes a variety of other polysaccharides. Unlike cellulose, these consist of a variety of different monomers and a branching buildup. In combination with pectins and most of all, lignin, hemicellulose forms the cell wall matrix in which cellulose fibers are embedded. In the course of plant development and aging, the share of the different components in the cell wall changes. From primary to secondary cell wall structures, the share of pectin and hemicellulose falls while the share of lignin rises.

Analytically the combination of cellulose and lignin can be found as insoluble substances in acid detergent (ADF: Acid detergent fiber). Approximately, this fraction is comparable to the former crude fiber content of the *Weende Analysis Standard*, which comprises a lesser detailed subdivision of substance groups.

Figure 7 shows the development of different substance groups during the generative phase from the example of a maize plant. The change of cob mass in relation to the mass of the rest of the plant due to an increased storage of starch becomes very obvious.



Biogas Production and Energy Crops. Figure 7

Development of the dry matter content (DM%) and substance composition of a maize plant from flowering to threshing ripeness (subdivided into cob and stover) ([21], complemented and altered)

Biogas Production and Energy Crops. Table 1 Substance composition of different energy plants for potential use in anaerobic digestion (Data from EVA – project [22, 23])

Crops	Crude Ash	ADL	Cellulose	Hemicellulose	Organic Rest	Crude Protein	Crude Fat	Starch	Sugar
Maize (early dough/dough)	4.3	3.4	23.1	22.8	9.5	8.0	2.5	15.6	10.8
Sugar beet, clean	16.6	0.2	21.0	21.6	0.6	15.9	2.1	0.0	22.0
Winter triticale WC (medium milk – early dough)	4.8	4.8	27.8	22.7	8.0	8.4	1.8	7.4	14.4
Clover grass first cut	9.8	2.8	28.2	11.8	17.4	13.7	3.0	1.6	11.7
Clover grass third cut	12.1	5.6	27.5	8.0	18.0	16.6	3.3	3.7	5.2
Cup plant	9.7				8.3	19.8	1.8		
Sorghum (<i>Bicolor</i> × <i>sudanense</i>) (up to early dough)	5.4	5.9	30.9	25.5	7.4	8.5	1.7	3.5	11.1

WC whole crop

At the same time, due to the transport and transformation of sugars as well as the lignification of the cell wall (characterized as crude fiber) and the digestibility of the stover sinks considerably.

Accordingly, Table 1 shows characterization of potential energy plant substrates for silage preparation. Values are given for “optimum” harvest dates for ensiling processes and anaerobic digestion.

Substrate Requirements and Biogas Yields Simple carbohydrates, fats, and proteins are the most accessible nutrients for bacteria involved in the process of anaerobic digestion. Thus, substrates containing high percentages of sugar and starch can be used to react quickly to low supply situations of the bacteria. Lignin, on the other hand, can be characterized as inert inside the fermenter and has no value for biogas production. Cellulose and hemicellulose form an interim position (Fig. 8). Also the digestibility of these groups can be limited by their being included in lignin–cellulose–hemicellulose complexes. In addition to the share of lignin, a mass of approximately 1.4 times this amount cannot be digested by the bacteria involved [24].

Planning of fermenter volume and the retention time or volume load is therefore also linked to the characteristics of substrates. The larger the share of slowly digestible substance groups, the larger the size of the fermenter to be constructed, in order to allow for an extensive digestion of organic matter (e.g., [25]).

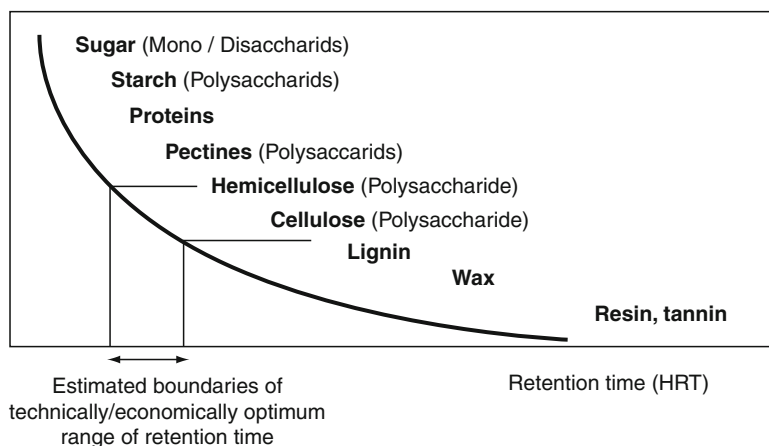
Additionally, in planning other parts of the biogas plant, the feedstock plays a major role. Feeding, stirring, and pumping/discharging technology should be chosen according to the characteristics of substrates, for example, regarding the tendency to form deposition or floating layers [27].

While these characteristics influence the investment cost, the direct revenue of feedstocks is largely depending on their specific biogas formation potential.

An approach to the derivation of the biogas formation potential is to be seen in stoichiometric calculations (e.g., [28–31]). According to these sources, the elementary composition of plant material (C, H, and O) allows for an approximate estimation of the gas formation potential (see, e.g., Table 2).

Due to the fact that values are calculated for a complete digestion of substances for the derivation of practically achievable yields, it is necessary to involve the actually digestible share of each substance group. One frequently used approach is to be seen in the utilization of digestibility coefficients known from feeding experiments, which are multiplied with potential methane yields (e.g., [32] based on [22, 30]). Despite various formulas that have been suggested (e.g., [33–35]), the usability for a wide range of plant and substrate types is limited in its validity, due to a so far non-sufficient parameterization for different plants and harvest stages.

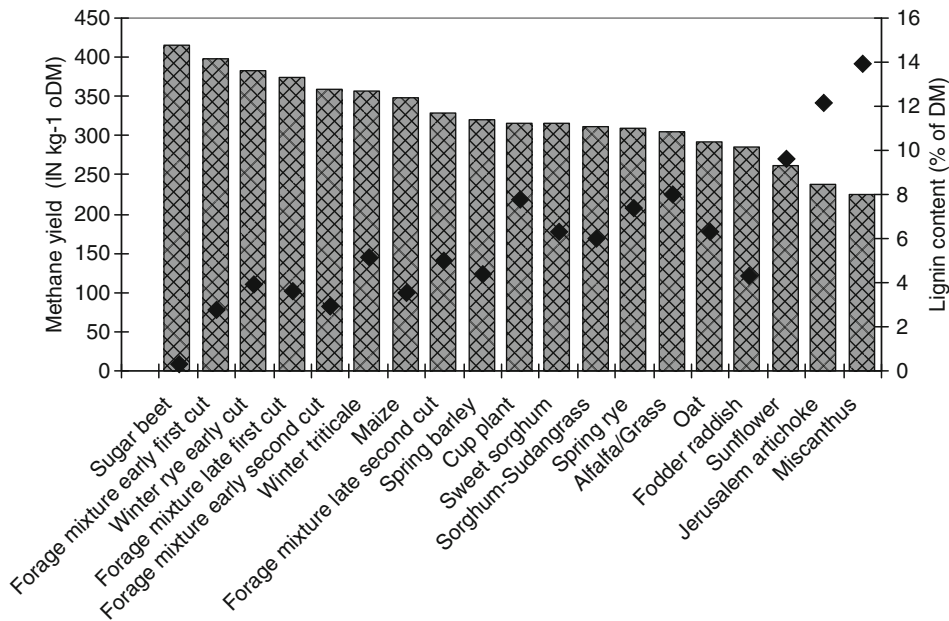
Another possibility is the identification of gas yields using laboratory methods, for example, the utilization of batch tests (e.g., [36]). Methane yields for different energy crop substrates are shown in Fig. 9. Based on findings from different plant species a correlation between methane yield and the lignin content ($R^2 = 0.78$) or the sum of lignin and cellulose ($R^2 = 0.60$) can be seen [37]. Low methane yields of the Asteraceae sunflower and Jerusalem artichoke as well as *Miscanthus* go along with high lignin shares in plant matter.



Biogas Production and Energy Crops. Figure 8
Digestion time of different substances [26]

Biogas Production and Energy Crops. Table 2 Potential and composition of biogas from different substance groups [31]

Substance group	Molar weight (g/mol)	Molar share of CO ₂ and CH ₄ in biogas (mol)	Molar volume of biogas (g/mol)	Potential biogas yield (l/g)
Carbohydrates C ₆ H ₁₂ O ₆ or (CH ₂ O) _n	180	3 CO ₂ + 3 CH ₄	6·22.4 = 134.4	134.4/180 = 0.746
Fats, e.g., Palmitin C ₁₆ H ₃₂ O ₂	256	4.5 CO ₂ + 11.5 CH ₄	16·22.4 = 358.4	358.4/256 = 1.39
Proteins incorp. 21 amino acids C ₁₃ H ₂₅ O ₇ (N ₃ S)	367	5.125 CO ₂ + 7.857 CH ₄	13·22.4 = 291	291/367 = 0.79
Plant biomass C ₃₈ H ₆₀ O ₂₆	932	18 CO ₂ + 20 CH ₄	38·22.4 = 851	851/932 = 0.91



Biogas Production and Energy Crops. Figure 9

Methane yields and lignin content of silages from different plant material. Values shown are identified according to VDI 4360 and do not include ensiling losses. ([37]; sugar beet according to [38]; cup plant calculated value according to [39])

Since minerals (ash) do not hold a proper methane formation potential, gas yields are given as the potential per unit of organic dry matter (unit: liters under standard conditions for temperature and pressure per kg of organic dry matter l_N/kg DM).

For the metabolic processes of bacteria, which are involved in the process of digestion, a variety of minerals are required. Roughly a relation of 600:15:5:1 of C:N:P:K is regarded as optimal [27]. A lack of availability of elements such as nitrogen

(C:N > 40) can limit the growth of bacteria. The same applies for potassium, sodium, calcium, and a variety of other trace elements (e.g., Co, Ni, Mo, Se, Fe). Optimum concentrations are commonly approximated at between 1 and 10 mg/l for iron, 0.005–0.5 mg/l for Nickel, 0.003–0.06 mg/l for cobalt, and 0.005–0.05 mg/l for Molybdenum. For co-digesting manure, a sufficient supply of bacteria is, in most cases, provided. With very high concentrations of nutrients, risks of inhibition of digestion processes rise.

Accordingly, nitrogen can lead to toxic reactions and the inhibition of bacterial activity by the formation of ammonia (C:N < 15:1). High sulfur values can lead to the formation of hydrogen sulfide, which – in sparsely adapted conditions in the fermenter – can lead to inhibitions at concentrations of 50 mg/l and above. Furthermore, its corrosive impact on copper and copper-compounds should be mentioned. Table 3 shows data on critical concentrations. It should be noted though, that vast interactions between

inhibitors limit the force of expression of single values. Additionally, bacteria involved are able to adapt to and, in some parts, even decompose some inhibiting compounds [40].

Apart from the crop used, substrate characteristics can also be influenced by the date of harvesting, the choice of which should aim at optimum yield and conservation properties (Fig. 7). Choice of crops can influence soil input into the fermenter, which can lead to deposition layers such as in the case of sugar beet (below). Furthermore, chopping size, which influences the surface area prone to microbiological attack as well as the tendency of a substrate to form floating layers, are factors influencing the fermentation process.

Production Systems for Different Energy Crops

Intensive breeding work and optimized production systems were able to contribute to a major increase in the yield of agricultural crops during the last decades. Therefore, many of the crops used for biogas purposes are crops known from food or feed production, which are harvested at the time of maximum biomass yields for silage preparation.

Besides crops from the family of *Poaceae* (true grasses such as maize, sorghum, and other cereals), leaf fruits like sugar beet can also be used. Currently, perennial types of the family of *Asteraceae* (aster family), *Malvaceae* (mallow family), and *Polygonaceae* (knotweed family) are also in discussion. *Brassica* (mustard family) types are not suitable due to high sulfur contents in the plant material.

Maize

Distribution and relevance Worldwide, maize (*Zea mays*) is one of the major agricultural crops. It belongs to the family of true grasses (*Poaceae*) and is a C₄-plant. Globally, it is dominantly cultivated for food production as grain maize. The cropping of maize in temperate climates could be extended largely by the development of adapted breeds that were developed during the last decades. In temperate climates, silage maize (SM) for fodder production (harvesting and ensiling at dough stage, Fig. 7) is of highest relevance. Regionally, the cropping area of maize has been increased by an increased biogas

Biogas Production and Energy Crops. Table 3 Critical concentrations of different inhibitors in biogas reactors. Shown in brackets are values for adapted bacteria populations [40]

Inhibitor	Critical concentration
Sodium	6–30 g/l (60 g/l)
Potassium	3 g/l
Calcium	2.8 g/l CaCl ₂
Magnesium	2.4 g/l MgCl ₂
Ammonium/ ammonia	2.7–10 g/l (30 g/l)/ 0.15 g/l
Sulfur	50 mg/l H ₂ S; 100 mg/l S ₂ -160 mg/l Na ₂ S (1,000 mg/l H ₂ S; 600 mg/l Na ₂ S)
Nickel	10 mg/l
Copper	40 mg/l; carbonate 170 mg/l
Chrome	130 mg/l; carbonate 530 mg/l
Plumbum	340 mg/l
Zinc	400 mg/l; carbonate 160 mg/l
Iron	Carbonate 1,750 mg/l

production (Fig. 2). To some extent, new breeds sold especially for biogas production are grown (see section “Breeding”).

Demands on site and climate Maize requires 200 mm of precipitation during its vegetation span, whereas the main demand is set during the flowering period. The crop is less demanding with regard to soil type; however, more importance is given to soil structure. A good supply of nutrients and water is only guaranteed if the soil is well penetrable for rooting. For germination, a soil temperature of between 8°C and 10°C is needed.

Temperature remains largely the limiting factor in temperate climates. Even precocious breeds demand minimum mean air temperatures of more than 13°C during summer months (May to September) [41]. Temperature sums can therefore provide information for choosing a breed adapted to the site-specific growing period. They are also used for harvest date prognosis models.

An international classification of maize breeds, albeit not specified by utilization purposes, is given by the three-digit FAO number. The first and second digits refer to ripeness classification and subclassification respectively. Under central European conditions, a difference of 10 units roughly describes a difference in ripening of 1–2 days [42]. Breeding approaches aiming at the provision of breeds for the specialized purpose of biogas production use breeding material with higher FAO classifications. Yield increases could be noted on comparatively warm sites. The difference in FAO numbers should not exceed 30–40 due to the danger of not reaching sufficient dry matter values of >30%.

Distinctive aspects of cropping system Commonly, sowing is done with single-seed sowing techniques with row distances of 75 cm. A low coverage level during early summer (around June) leads to a comparably high exposure to the increasingly erosive precipitation. Accordingly, on sites with a slope of more than 5%, erosion risks have to be taken into account. These risks can be encountered by using lower row width, under-sown crops, or non-tillage systems. Non-tillage systems can be well used after the harvest of a winter (first or inter-)crop for the establishment of maize. To avoid yield risks, slow

development in early growth stages also makes weed control necessary.

Some investigations point out an influence of the harvest date on the specific methane yield of maize, while other results show no significant changes within the possible harvest time [43, 44]. Despite the possibility of higher methane yields (l_N/kg oDM) at early stages, investigations have shown that dry matter increment during the ripeness phase makes higher overall methane yields per hectare possible [35, 43], so most probably, substrate quality issues for ensiling (maximum 35% DM) determine optimum harvest date.

Apart from the high efficiency in using available water resources, the nutrient efficiency of maize is also very high. Per ton of dry matter, a withdrawal of 11–13 kg N, 2.1–2.6 kg P, 12–13.5 kg K, 2.5–3 kg Ca, and 1.8 kg Mg is a common range for analysis and for the estimation of the required amount of fertilizer.

Sorghum

Distribution and relevance Sorghum, just like maize, is part of the true grasses (*poaceae*) family and a C₄-plant. Cropping of sorghum is most relevant on the African continent, where it is mostly grown for grain utilization for food purposes. In the USA, sorghum is also highly relevant for silage preparation especially in the regions of the Great Plains where other fodder crops risk high yield losses due to summer drought. *Sorghum bicolor* and *Sorghum sudanense* as well as hybrid breeds of *Sorghum bicolor* and *Sorghum sudanense* are currently discussed and tested as substrates for biogas production.

Demands on site and climate The different sorghum types have a much higher demand regarding temperature conditions in comparison to maize. For germination, minimum soil temperatures of 14°C are needed [45]. Temperature sum from May to October should at least add up to 2,000°C (>5°C) [46]. Sorghum is frost-susceptible: Below temperatures of 4°C, it can suffer cold injuries.

To develop its characteristic rooting, sorghum breeds require deep soils without compactions. Despite slower root development, the subsequent deep rooting makes it possible to adequately utilize soil water and hence leads to good drought resistance properties and very fast growth during summer months. Compared to

maize, this is one of the decisive advantages of sorghum breeds (e.g., [47, 48]).

Experiments in Central Europe show a high yield potential for sorghum breeds. In many cases, the duration of the vegetation span was not sufficient for the development of sufficient dry matter values [49].

Distinctive aspects of the cropping system Sowing can be done with standard drill sowing techniques at a depth of about 2–3 cm. After a rather slow development in early development stages (especially in low temperature conditions), sorghum breeds show a rapid growth. In contrast to maize, sorghum tillers with 2–3 (bicolor – breeds) or 4–6 (*sudanense*/*sudanense* × *bicolor* – breeds) shoots respectively. *Sudanense* and *sudanense* × *bicolor* types can potentially be harvested more than once a year. Advantages in yield are not to be expected under Central European conditions and dry matter contents will not be reached in any of the cuts.

The height of sorghum breeds can exceed 4 m; however, it should be mentioned that tall-growing breeds often lack a sufficient stability. Sorghum shows a good appropriation of nutrients and can accordingly, similar to maize, make use of organic fertilizers. Withdrawal of nutrients for silage sorghum equals approximately 11 kg N, 4 kg P, 12.5 kg K, 1.5 kg Ca, and 1.2 kg of Mg per ton of dry matter.

The high sugar content of more than 20% for many *bicolor*-breeds (which are also specified as *Sorghum bicolor* ssp. *Saccharatum*) [50] lead to comparatively good ensiling properties. On the other hand, the lignin/crude fiber content is comparatively high, which leads to methane yields per mass unit that are around 10% lower than those of maize. In some breeds, there are high values in hydrocyanic acid, which are problematic for utilization as fodder but however do not inhibit anaerobic digestion properties [51].

Whole-Crop Cereals

Distribution and relevance Whole-crop cereals are cereals yielded from the early milk stage for silage preparation by the utilization of the entire plant matter. Generally, all cereals that are productive in market cereal production are suitable for this utilization purpose. In Central Europe, this encompasses predominantly wheat, rye, triticale, and barley. Due to their higher yield

expectancy, winter forms are preferred for substrate production. Grain-straw ratios in earlier literature suggested a high yield potential of the summer-annual oat; though, this could not be confirmed in testing newer breeds [49].

Demands on site and climate Winter forms of cereals are sown in autumn and demand the impact of cold temperatures during early growth (vernalization) to be able to proceed to the generative phase. This period of cold temperatures is shorter in winter barley (20–40 days) than in winter rye and winter triticale (30–60 days) and winter wheat (40–70 days). Spring forms of cereals do not demand vernalization and are sown as early as possible in spring (Central Europe: March). The gradation in genotype disposition, in terms of temperature demand and photoperiodic reaction, therefore play a major role for the question of suitability.

Germination of cereals starts at low temperatures. Rye has the lowest demand with temperatures of 1–3°C. Minimum temperatures for the net primary production of most cereals are around 3–5°C, and for oats between 4 and 6°C. Winter hardiness differs between the different types of cereals. While winter rye can sustain snowless frost periods with temperatures of up to –25°C, temperature values of around –20°C for winter triticale and winter wheat and of around –15°C for winter barley can be sustained. After field emergence in spring, oat can also sustain frosts of –6°C.

Winter wheat has the highest water and soil requirements and – when provided – shows high productivity. On lighter soils, rye can produce yields similar to those of winter wheat. Barley also has fairly low requirements concerning soil quality. Triticale, as a cross of wheat and rye, was supposed to combine the relatively low requirements of rye with the high yield potentials of wheat. High whole-crop yield potentials on sites providing good soil characteristics can be confirmed. Since the crop ratio of comparatively high-yielding wheat is already high on accordant sites, winter triticale is being recommended because in addition to its high-yielding potential, its cultivation provides possibilities to extend crop rotations (see section “[Cropping Systems](#)”). On low-yielding sites, winter rye has the best suitability in whole-crop cereal production as

well. Rye shows higher self-compatibility than wheat, which lowers the necessity for alternatives.

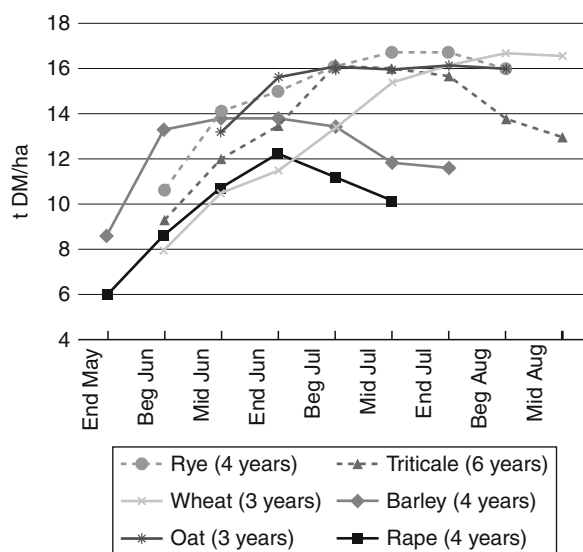
Winter cereals, just as other C_3 -plants, commonly have lower water use efficiency than C_4 -plants such as maize or sorghum. The decisive advantage of winter annuality is that in temperate climates, during tillering and stem elongation stages, these plants can convert winter precipitation stored in soils much better into biomass.

Distinctive aspects of cropping system In general, cropping systems for cereals aimed at substrate production are to be oriented at market cereal production. From an agronomic point of view, during the last years, various options to reduce factor intensity have been discussed. These discussions were based on the changed quality requirements and the shorter growing periods of whole-crop cereals (see section “Factor Intensity”).

Biomass yield of cereals can increase until the stage of yellow ripeness. From then respiration of assimilates and loss of leaves lead to a net yield reduction [52]. For the choice of harvest time, considerations on intended silage quality and the establishment of a subsequent crop play a major role. For instance, during yellow ripeness, dry matter contents exceed the optimum range in many cases. Accordingly, simultaneous optimization of yield and ensiling properties, brings about short time frames for harvesting in most years at the end of milky stage. Since the correlation between dry matter content and the development stage is low, tentative testing of plant material before harvest is advisable. From the viewpoint of crop rotation design, harvest time can also be influenced by the choice of cereal. Winter barley reaches an optimum harvest time much earlier than winter wheat (Fig. 10).

Depending on the type of cereal and the harvest stage, withdrawal of nutrients from the early milk stage amount to 11–15 kg N, 2–2.5 kg P, 14–17.5 kg K, 0.9–1.2 t Mg, 2–3.2 kg Ca per ton of dry matter.

Cropping systems for whole-crop cereals should not be mistaken for intercropping systems. Green-cutting of rye, for which special breeds are sold, starts from the visibility of the first awns. Yield quantity can be approximated at around half of the yield of whole-crop yields. Due to low dry matter contents, swathing and pre-wilting is required in many cases.



Biogas Production and Energy Crops. Figure 10
Development of dry matter for winter rape, barley, rye, wheat, triticale, and oat on central German sites [52]

Yields of winter cereals vary, depending on site characteristics, according to grain production largely. On loess-influenced sites, yields of up to 20 t DM can be achieved. On sandy soils, yield expectations are approximately half of this value. Despite these major differences between the different sites, intertemporal yield variations on the specific sites are lower than those of maize.

Sugar Beet

Distribution and relevance Sugar beet (*Beta vulgaris* ssp. *maritima*) is mainly grown in Central Europe. As the beet may take advantage of large parts of the available vegetation period of temperate climates, it is one of the most yielding crops in those regions. Due to the reform of the Common Market Organization for sugar in 2006, sugar beet cropping for sugar production has sensibly gone down. As expertise and machinery still exist, there is growing interest for the utilization of sugar beet for other purposes. Therefore, technical equipment and machinery must be adapted correspondingly.

Other than sugar beet, fodder beet is of less importance. As they have low dry matter contents and the existing varieties lack resistance against Rhizomania,

leaf spot, or nematodes, it is at present not of interest to grow fodder beet for biogas production.

Demands on site and climate Sugar beet cropping is done best on deep, medium-heavy soils that allow good rooting. Therefore, chernozem and brown earth with loess with a stable soil structure and a high, usable field capacity are particularly well suited. From the point of view of substrate production, keeping troublesome substances away from the digester is an issue of decisive importance. Beets from sandy soils have less soil tare, while loam, clay, or silt adheres more easily to the beets. However, practical experience has shown that such particles stay in suspension due to agitating and pumping in the digester; they stick to organic matter and thus leave the digester with the residues. Sand, however, tends to sediment and form a layer. Another problem, which is much more dangerous, arises from stones, as they might damage the feeding system and the agitators. Therefore, cost-saving technologies to remove hazardous material before it gets into the digesters will be of decisive importance in the future. At present, mobile units to clean the beet are being developed.

Distinctive aspects of cropping system The sugar beet is drilled in rows with a special precision drill as soon as the soil is well settled and dry, and night frosts are not any more to be expected. It is better to drill later instead of disturbing and hindering the sugar beets' growth by soil compaction as a consequence of the wrong soil management.

In conventional sugar beet cropping, the extraction rate per ton of dry matter is around 8 kg N, 1.8 kg P, 9 kg K, 2.2 kg Mg (the root) and/or 22 kg N, 2.8 kg P, 27 kg K, and 3.3 kg Mg (leaves). The quality parameters of sugar production do not apply to sugar beet cropping for biogas production; fertilization programs may thus be modified. More nitrogen fertilization leads to disproportionate increase of leaf growth compared to root growth. Nitrogen fertilization should not be increased by more than 20% with regard to the level applied for sugar beet for sugar production. It may be that boron could be necessary at canopy closure to prevent from heart and root rot, especially if the beets are supposed to be stored in field clamps for a longer period.

Other than for sugar production, the grown biomass of beets should be used completely. When defoliating the beets, they are not topped but only stripped of their leaves, and the crown is harvested together with the root. This allows a surplus yield of 5–10% [53]. However, when using this method, sugar beets should be fed into the digesters before too long, as the leaves may start to regrow. Sugar beet leaves are to be considered an additional yield factor, as the leaves mean an additional fresh matter yield of around 3.5–4.0 t of dry matter/ha, the equivalent of up to 15% more methane yield per hectare. But as leaves contain less energy than the roots, in general only short transport distances are profitable.

As sugar beets have a low dry matter content and are therefore less suitable for silage, bridging the time between the moment the beet is mature and the moment it is fed into the digester constitutes a certain challenge.

Storing the fresh beets in clamps and feeding them into the biogas production plant is possible between the months of September through mid-February under Central European conditions. However, clamps should be covered by mid-November. When clamps thaw after long periods of frost, the beets should be processed as soon as possible. At present, it is checked whether the beets may remain in the soil during winter and be harvested before bolting. Compared to storage in clamps, relatively mild winters thus allowed gaining yield surpluses of 10% [54]. With less favorable conditions and strong ground frosts, however, it is necessary to harvest and process the beets as quickly as possible.

When beets are to be stored for a longer term, they must be ensiled. The latest findings open up the following possibilities:

1. Ensiling in plastic tunnels: Up to now, good experiences have been made with ensiling whole beets. Chopped beets in foil tunnels would run the risk of causing the tunnel to burst due to the resulting seepage.
2. Ensiling entire beets in bunker silos: The density of the sugar beets changes in the course of the ensiling process. The piles slump down to almost half the height during ensiling. Sampling of such beets has shown pH-values of 3.5. In any case, it is important to collect the seepage.

3. Ensiling as mixed silage with maize: Good experiences have been made during the past years with mixed silage (maize/sugar beets in layers with a ratio of up to 50/50) in bunker silos. The main challenge consists of finding an optimal harvest date for sugar beets and maize, and coordinating two harvesting processes for different crops at a time. For example, in large parts of Germany, maize is harvested during mid-September until the end of the month – a time, where sugar beets have not yet reached their maximum yield. Therefore, a late maize variety should be chosen (see section “Breeding”). Another possibility is ensiling beets together with dryer substances, for example, ground ear maize (GEM). In such cases, even a ratio of up to 70% of sugar beets would be possible.
4. Ensiling in existing tower silos: If tower silos already exist, they are useful. Main stress should be put on producing beet pulp which is as homogeneous as possible, to avoid sedimentation in the silo.

Depending on the storage method, it is necessary to provide for adequate chopping technique before and/or after storage. Practical experience has shown that when whole beets are stored, it is sufficient for fermentation needs to chop the beets to a size of 3–4 to 1 cm, to take advantage of the specific properties offered by sugar beets for biogas production.

These favorable properties are quick fermentation (Fig. 8), high methane yields (Fig. 9), easy pumpability, and a process-stabilizing influence compared to the specific acid values prevailing in biogas plants despite quick acidification in the digester when sugar beets are fed in [55].

Perennial Forage Grasses and Forage Mixtures

Distribution and relevance Multi-cut forage crops consist of annual and perennial grasses, small-seed legumes or mixtures including various types. In Europe, these were traditionally grown to provide protein-rich fodder for dairy cows. Due to the expansion of maize cropping, the crop ratio of perennial fodder plants decreased largely [42]. In Europe, grasses cultivated include mostly species from the *Poaceae* subfamily of *Pooideae*, mainly ryegrass (*Lolium*), Festuca (*Festuca*) and hybrid crossings (*Festulolium*) accordingly as well

as Timothy grass (*Phleum*) breeds and cocksfoot (*Dactylis glomerata*).

During the last years, perennial warm-season grasses of the *Poaceae* subfamily of *Panicoideae* such as Miscanthus (*Miscanthus Giganteus*), Andropogon (*Andropogon gerardii*), or Switchgrass (*Panicum virgatum*) were also tested for energy cropping in temperate climates. According to current knowledge, good yields can be achieved with warm-season grasses. For the utilization as a biogas substrate an extensive lignification (Miscanthus, Fig. 9), a lack of persistence or a high damage from early cuts proved to be disadvantageous [56]. As such, other conversion routes are more reasonable (see other article, e.g., on combustion).

Demands on site and climate Production of grasses and forage mixtures can be set on all arable sites. Mostly, it is advantageous on sites that are too cold for the cropping of maize or sorghum or where late frosts in spring or early frosts in autumn are to be expected. For the cropping of red clover (and grass mixtures), continental sites with average precipitation levels of 650 mm are most suited. Ryegrasses show suitability on fresh to moist sites with precipitation of more than 650 mm. Alfalfa (and grass mixtures) are advantageous on anhydromorph calcareous soils and weathered loess soils. Alfalfa and cocksfoot are also advantageous on drier sites.

Distinctive aspects of cropping system For an optimum choice, apart from site characteristics, the planned utilization period is of major importance. Generally, the cropping of mixtures is preferable due to weather and utilization conditions, risk minimization, and their higher adaptation potential to the specific site. Furthermore, the nitrogen fixation of mixtures, including legumes, as well as the positive impact of perennial grasses and mixtures on the humus balance should be included into the evaluation.

The choice of cutting frequency influences the specific methane yield as well as the yield of perennial forage cropping. In later and hence reduced cutting during the vegetation span, substrates may on the one hand become less digestible. On the other hand, yield increases. According to current knowledge, reduced cutting frequency, which means 3–4 cuts instead of 4–5 cuts can be advantageous and lead to a 10% increase in overall methane yields per hectare [57–59].

Due to the low dry matter content of the cuts of grasses and forage mixtures, fresh material shows low suitability for ensiling. Commonly, swathings and pre-wilting to a dry matter content of 30% is done before the work step of picking up under the precondition of sufficiently warm conditions.

Overall, during the main utilization years, yields of ryegrass mixtures on maritime influenced sites can exceed 20 t DM/ha, on better but in summer dryer continental sites, yield of 16 t DM/ha can be achieved. Multi-cut systems including production steps for swathings demand higher production costs per hectare. Due to low income of fodder production from permanent grassland, the utilization of these sites for energetic purposes might increase as well [60, 61].

Additional “New” Energy Crops Given the specific substrate requirements of the utilization pathway of anaerobic digestion, during the last years, the cropping of a range of other energy crops that have no or only little share in current cropping systems of temperate agricultural regions has been discussed. Whereas knowledge on the cropping of some of these plants as the cup plant (*Silphium perfoliatum*) or the Jerusalem artichoke (*Helianthus tuberosus* L.) exists, for other options, very little experience is reported.

Cup Plant (*Silphium perfoliatum*) The cup plant is a perennial plant of the aster family (*asteracea*) that originates from the temperate regions of North America. While little experience in agricultural cultivation has been made there, the plant was tested in the 1970s and 1980s in Japan, Russia, and Eastern Germany among others concerning its properties as a fodder plant [62]. Due to lack of seed production, cultivation could not be implemented practically.

Demands of the cup plant with regard to soil texture is not high; it can also be cultivated on sandy soils at fairly low annual precipitation levels of 350–440 mm. Water-logged soils are not suitable; best growth can be expected on humus sites with good water supply. For germination, seeds require a longer phase of cool or changing temperatures.

For the establishment of practically applicable cropping systems, current works focus on the pretreatment of seed and single-seed sowing techniques – currently establishment has to be done,

using seedlings. During the year of establishment, plant development is slow and no linear growth takes place. Weed control is necessary. Planting should be finished at the beginning of June, to tap the full yield potential from the second year on. As a utilization period, a 15-year period is currently being focused on. Nutrient withdrawal amounts to 10 kg N, 1.9 kg P, 16–17 kg K, and 4 kg Mg per t DM.

Harvesting starts from the flowering period at dry matter contents of 28–30%. Ensiling properties are good and deliver methane yields that are slightly lower than those of maize at 300 l_N/kg DM (Fig. 9). Yields of 17–20 t DM/ha from the second year on better soils [39] and 12 t DM/ha on weaker soils [63] can lead to the appraisal that the cup plant might in future be a new crop for energy production in temperate climates.

Jerusalem Artichoke (*Helianthus tuberosus* L.) Jerusalem artichoke is, like the cup plant, part of the aster family (*Asteraceae*). Instead of starch, the plant uses Inulin, a fructose-polysaccharide, as a reserve carbohydrate. This is stored in irregularly shaped tubers measuring up to 10 cm in diameter from which several pith-filled stems of up to 3 m in length are formed.

Jerusalem artichoke also grows on sandy soils and shallow alteration soils. High yields require a good water supply during summer months. For the utilization of the tubers, the same restrictions apply as for the utilization of sugar beet. This means, that sites should be avoided, that entail an intensive input of soil, especially sand and stones into the fermenter.

Since plants do not reach seed ripeness in temperate climates, reproduction is done vegetatively using potato planters for the deposition of tuber. Choice of breeds and planting density depend on the utilization aim. For the utilization of aboveground biomass, the planting density is lower (about 40,000 tubers/ha) than for the utilization of tuber biomass itself (45,000–50,000 tubers/ha). Nutrient withdrawal ranges at approximately 10–12 kg N, 2–3 kg P, 23–25 kg K, and 2 kg Mg per t DM of tuber and 7.5 kg N, 0.8 kg P, 20–21 kg per ton DM of the aboveground biomass respectively.

By leaving the tuber in the soil, the utilization of the aboveground biomass can be done for several years. Haulm biomass ranges between 10 and 16 t DM/ha. From the second year onward, stands have to be thinned to prevent yields from decreasing. Yielding of

tuber can be done with potato harvesting technology. At the optimum stage, yields of the tuber range between 6 and 8 t DM/ha. If tuber and haulm is to be harvested, a compromise between maximizing tuber yield and the earlier maximization of haulm yield has to be found. Concerning the tuber, just as for sugar beet ensiling can be a challenge. From a cropping perspective, regrowth even from small tuber parts remaining in the soil may cause problems in the successive crop. While methane yields of haulm biomass is relatively low due to lignification (Fig. 9), the tuber can reach methane yields of up to 400 l_N/kg DM [64].

White sweet clover (*Melilotus albus*) The cropping of the biennial White Sweet Clover is currently being discussed on sites that fall below the suitability for Alfalfa or Red Clover. According to current knowledge, under Central European conditions, it can reach yields of up to 7 t DM/ha on these sites, which is around 30% lower than the comparable yield of maize. On better sites, yields of 10.1 t DM/ha were stated [65]. Additionally, an extensive fixation of nitrogen (90–150 kg/ha) and intensive and deep rooting (Root biomass of 12–18 t DM/ha) have to be included into the evaluation. On the other hand, the methane yield of below 275 l_N/kg DM is comparatively low. White sweet clover (*Melilotus albus*), which originates from Eurasia, is assessed as invasive and problematic in many parts of North America.

Rumex Originating from Ukraine, the cross of *Rumex patencia* und *R. tianschanicus* can be cultivated using standard drill technology. Utilization of cultivation material from the second cropping year can be carried out for 15–20 years in two cuts per year. Sufficient dry matter contents at the harvesting stage should be aimed at. Current results show yields of 9 t DM with low dry matter contents and hence no explicit suitability as biogas substrate [66].

Virginia Fanpetals Virginia Fanpetals (*Sida hermaphrodita*) is a perennial crop, which has little demands concerning site condition and shows strong winter hardiness [67]. On a sandy loam yields of the second and third year of cropping equaled 11 t DM/ha (Ibid.). On Eastern German loess sites, yields of the second cropping year were between 5 and 9 t DM [66] and 12 t DM [68].

Polygonum Cropping experience of the species originating from Northeast Asia is limited. Up to 25 t DM for *P. sacchalinese* can be achieved [56]. The large leaf biomass (LAI 18–25) makes stands vulnerable to hail damage. Lower yield, which is on average slightly lower than for maize, were recorded for *P. weyrichii* [69].

It should be noted that *P. sacchalinese* is closely related to *P. japonicum*. In North America and Europe, *P. japonicum* is one of the most problematic invasive species (www.issg.org). Due to the fact that *P. sacchalinese*, similar to *P. japonicum*, has an invasive root system and thus proves to be hard to control, and more so since it can hybridize with *P. japonicum*, cropping is not advisable.

Breeding (Author A. Von Felde)

In the past efforts in breeding of agricultural crops had been concentrated exclusively on progress in foodstuffs and animal feed production, mainly for the production of starch, sugar, and oil. Maximizing the production of energy with environmentally sound and resource-friendly cropping methods constitutes a new breeding goal, which expectedly will be honored by impressive results and successes within a short time. Energy maize (EM) breeding can serve as one example (Fig. 11).



Biogas Production and Energy Crops. Figure 11 Biomass yield potential of maize: Three German, one Italian, and one Peruvian maize variety (left to right) in an energy maize performance test near Wesel in 2004

The example of maize allows illustrating the enormous increase possible in biomass and therefore energy production within a short time period due to breeding efforts, if breeders do not think any more in categories typical for grain and silage use. Freed from those restrictions, new ways may be opened. Such new approaches will make it possible to increase the total dry matter (TDM) yield of maize from today's 15–18 t/ha to more than 25 t/ha. This equates to a methane output of more than 8,000 m³/ha, or a petrol equivalent of 8,000 l/ha. Figure 11 gives an impression of the biomass yield potential of maize, potential to be exploited in breeding and plant production.

The following breeding approaches may be used to increase biomass production and subsequently energy production of maize:

1. Prolongation of the phase of vegetative growth
2. Combination of late maturity and cold tolerance through breeding
3. Integration of short-day genes from exotic populations

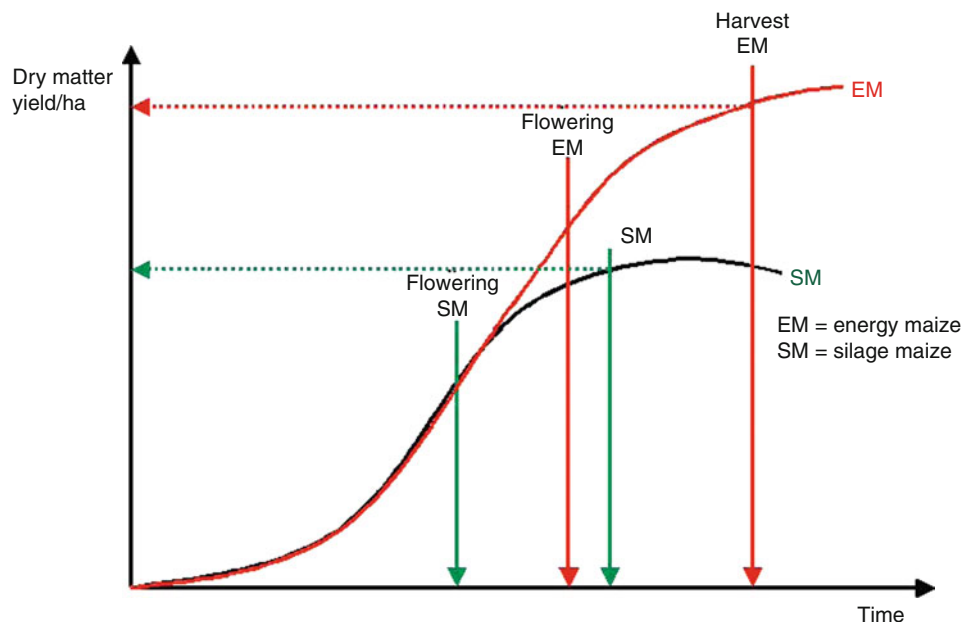
These methods are completed by further long-term breeding goals, for example, improvement of

drought tolerance, adaptation of maize to a C₃/C₄ energy crop rotation, and adaptation of energy maize to the conditions of organic farming (by striving for robustness and competitiveness in mixed and underseed cropping).

Prolongation of the Vegetative Growth The simplified graph in Fig. 12 illustrates the reasons for which the approach of prolonging the phase of vegetative growth promises to increase the biomass potential and therefore the energy potential. The black curve (Fig. 12) depicts the course of total dry matter production of a maize variety which has been bred for silage use (SM = silage maize). The red curve shows the development of a maize variety which has been optimized for energy production through breeding (EM = energy maize).

As starch and cellulose offer the same specific methane yield, an increased vegetative growth phase of stem and leaves as such is not necessarily disadvantageous (reduced starch content).

Until the flowering of the silage maize variety, both growth curves show an identical shape. The vegetative total dry matter of both varieties increases exponentially.



Biogas Production and Energy Crops. Figure 12

Formation of total dry matter (TDM)-yield in a silage maize (SM) variety and an energy maize (EM) variety

After the flowering of the silage maize variety, however, both growth curves increasingly diverge. The silage maize's curve has a linear growth and soon flattens, while the energy maize's growth curve continues with its exponential growth. This further growth is due to the simple physiological fact that the energy maize variety continues to invest its assimilation performance in supplementary vegetative leaf mass instead of investing it in ear production, which is what happens with the silage maize variety. These supplementary leaves contribute to assimilation in the energy maize variety, while the carbohydrates stored in the silage maize variety's ears do not. This explains the superiority of the energy maize variety's yield compared to the silage maize variety's yield. The later the energy maize variety is harvested, the more pronounced its superiority compared to silage maize.

This relatively simple physiological trick of prolonging the phase of exponential growth of the plants by postponing the flowering time helps to achieve enormous increases in yield not only for maize, but as well for most of the crops.

Late Maturity and Cold Tolerance Basically, it is easy to postpone the flowering time of maize varieties.

For example, the only thing to do is to change the maturity groups cropped in Southern France, Hungary, or Italy and one immediately has breeding material at hand that flowers sufficiently late, which is what is needed for energy maize cropping in Germany.

Unfortunately, there is a big drawback regarding the breeding material groups used in such regions: They are not adapted to the cold climate and therefore do not show enough development during the early stages. All the recent hybrids from Southern European breeding programs have been tested most intensively under German as well as Dutch cropping conditions to find out whether they are suitable for energy maize hybrids. In 3 out of 4 test years, some of the Southern European varieties (and some of them even clearly) outmatched the best conventional German silage maize varieties. The only exception was the year 2004, which was extremely cold. Due to the very cold spring, practically all the Southern European varieties fell strongly behind (Fig. 13) as they had a bad initial development compared to the German silage maize varieties. In general,

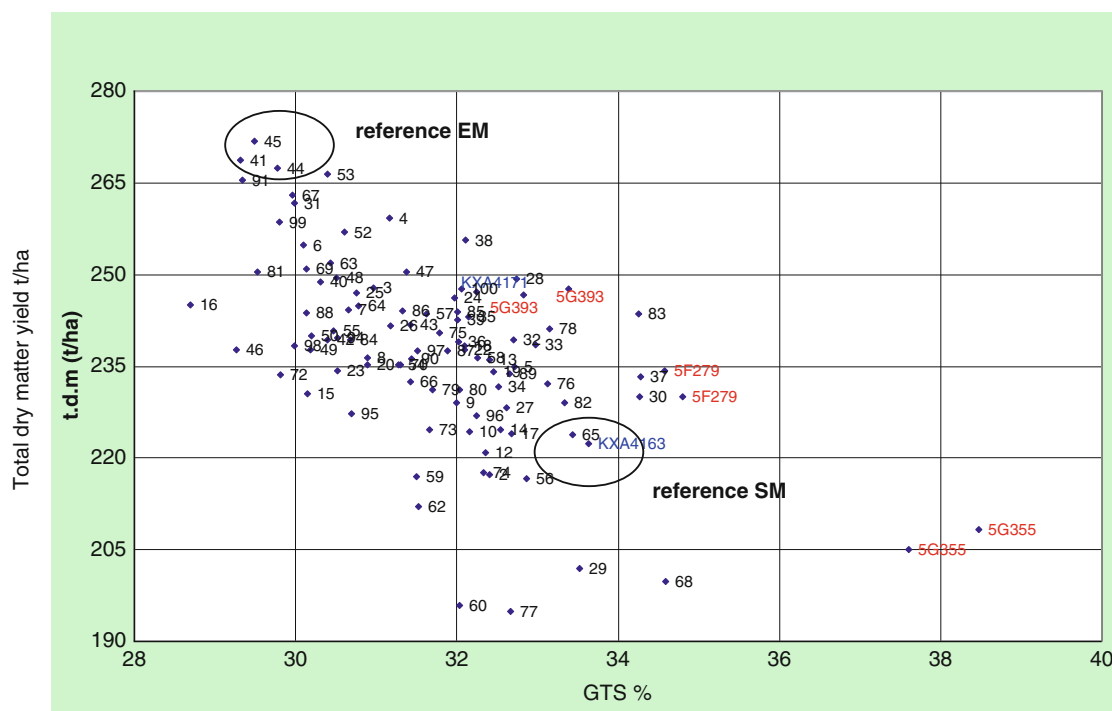


Biogas Production and Energy Crops. Figure 13

The cold-tolerant German standard variety GAVOTT (on the right side) surrounded by numerous cold-sensitive Italian hybrids, photographed in July 2004 in an energy maize performance test in Wesel

this backwardness was so important that they were not able to compensate during the warmer summer months.

Therefore, breeding is called to unite late maturity and cold tolerance in energy maize hybrids. One of the obvious ways suggesting themselves is to start selecting for cold tolerance where full genetic variance is still available, which is not the level of varieties, but the level of breeding lines, which is one level earlier. At that stage, the material is not yet limited as it has not yet been checked about its ability to be combined. Figure 14 illustrates the performance of experimental crossings of 90 South European lines, which had been selected sharply. They were tested in one out of three ten times ten-lattices together with ten standards regarding their combinability with a German flint tester of a conventional silage maize breeding program. This test was carried out at Bernburg and Wesel, both German places, and also at two Dutch places. Three elite lines were tested twice together with those lines: the early German line 5G355, the medium-early French line 5F279, and the medium-late German line 5G393. The results show that it is possible to reach new yield performances of 27 t/ha with Southern European DH-lines, which have been selected for cold tolerance. This is a level that is not even reached by the presently best-performing German silage maize breeding



Biogas Production and Energy Crops. Figure 14

Dry matter yield (DM in dt/ha) as a function of the maturity of the entire plant (DM in%) of 90 new energy maize hybrids (and 10 standards) from late, Southern European lines which had been selected for cold tolerance and crossed with a German flint tester. Reference SM - Silage maize for fodder production; Reference EM - Potentiale "Energy Maize" - Breeds showing higher yield potential

material, which is represented by the three elite lines in the diagram. The late hybrids' dry matter content amounting to 30% guarantees safe ensiling without seepage and simultaneously offers good methane output. When trying to assess these results, it should be taken into account that the progress in breeding was achieved by improving just the female side of the experimental crossings, as the pollinizer used (= father) had been a line from conventional European silage maize breeding programs.

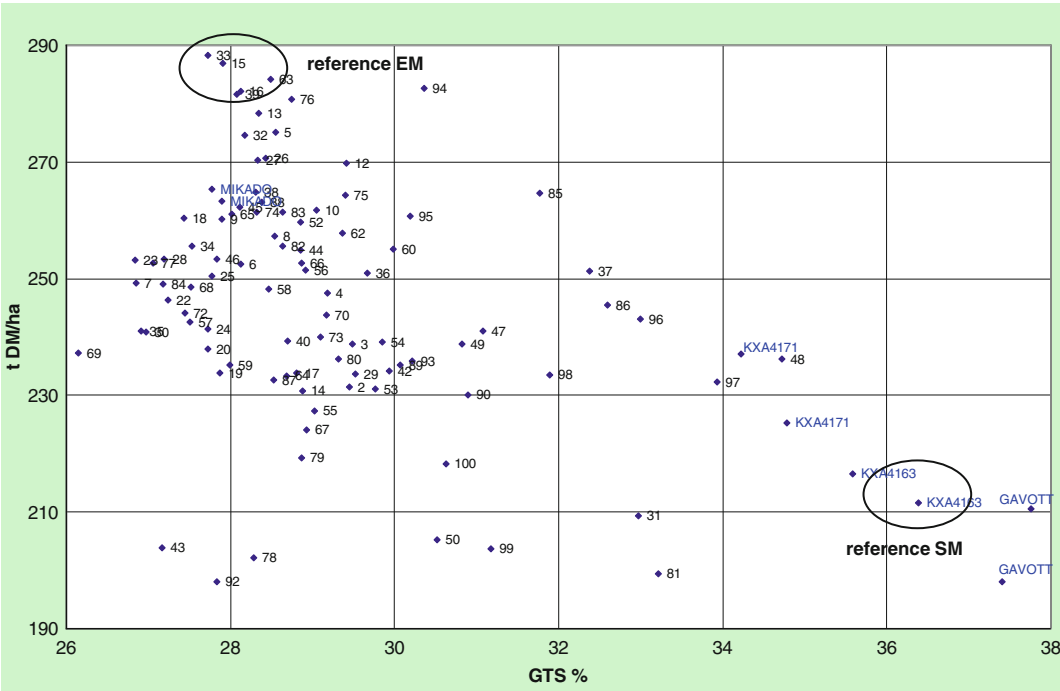
The results shown in Fig. 14 are representative for the further about 180 Southern European lines tested in the two further ten times ten-lattices with a German flint tester. They confirm the results of both previous years, where Southern European lines had been evaluated the same way, and with the same results [70, 71].

An obvious possibility is to cross Southern European lines, which had been selected previously for their cold tolerance, among themselves in order to

maybe achieve energy maize hybrids that are even more yielding. Therefore, the best Southern European lines, which had been identified in energy maize trials, were used to produce and test around 250 factorial crossings. The best performances of these hybrids reached 28 and 29 t/ha. They achieved a level of performance, which was about 7 t/ha higher than for instance the yield potential of the hybrid KXA 4163 (Fig. 15).

Integration of Short-Day Genes from Exotic Populations

There is another, and quite different, way of increasing biomass and therefore energetic performance of maize. If South American or Central American maize populations adapted to tropical short days are cropped in Central European long-day climates, those populations react with increased vegetative growth. Some of these exotic maize breeds reach heights of 4–5 m (Fig. 11). But not only the length of the stem is increased, but as well its diameter (Fig. 16).



Biogas Production and Energy Crops. Figure 15

Dry matter yield (DM in t/ha) as a function of the maturity of the entire plant (DM%) of 90 new energy maize hybrids (and 10 standards) from a factorial of late, Southern European DH-lines which had been selected for cold tolerance. Reference SM - Silage maize for fodder production; Reference EM - Potentiale “Energy Maize” - Breeds showing higher yield potential



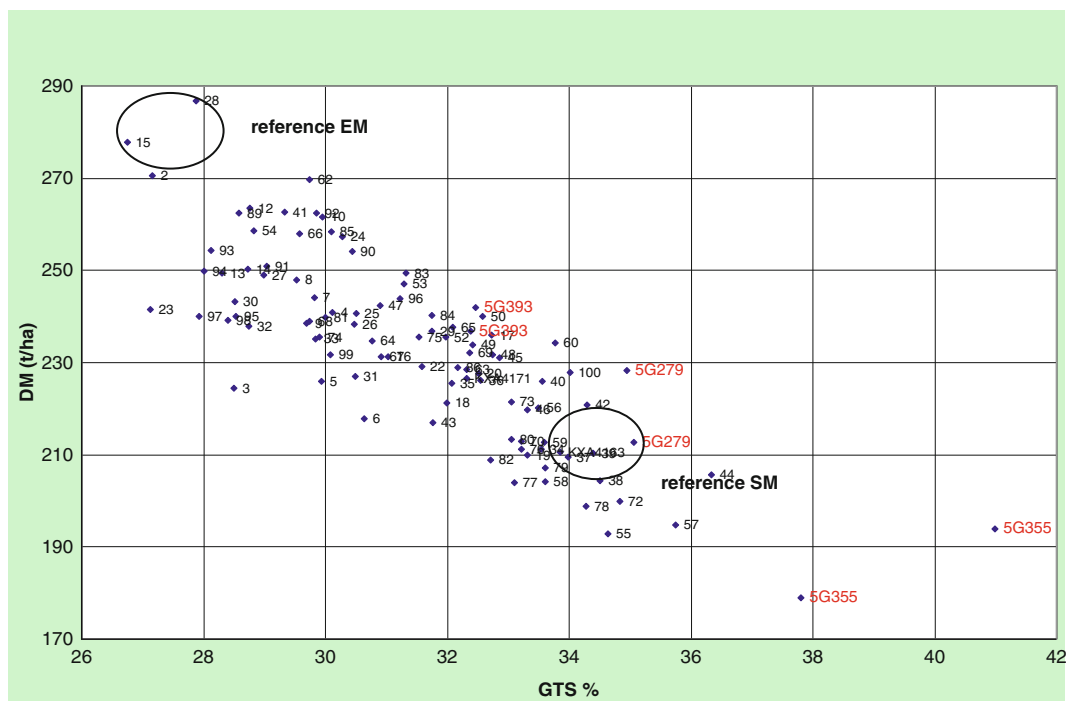
Biogas Production and Energy Crops. Figure 16

Comparison of stems from a German, Italian, and Peruvian breed [72]

Therefore, it seems reasonable to check the effect of such genetically steered growth regulation mechanisms in an energy maize breeding program. If photoperiodic sensitivity (short-day reaction) is fixed on the female side as well as the pollinizer side of energy maize hybrids, their vegetative mass performance may be

improved considerably. Integrating such short-day genes proceeding from Mexican sources for the female side, and from Peruvian sources on the pollinizer side, guarantee, that heterosis between female and male gene pools is conserved.

In Fig. 17, the yields of 90 energy maize hybrids are shown. They contain new German–Mexican inbred lines on the female side, and a conventional flint tester from the silage maize breeding program on the pollinizer side. All of the German–Mexican inbreeds consist 75% of the German dent elite line 5G355 and 25% of gene material of Mexican origin. The superiority of the new German–Mexican inbreeds compared to the recurrent parent 5G355 is visible; they are yielding up to 10 t/ha more. This is superiority to an unexpected extent and surprising at first sight. As soon as the individual performance of the lines is checked, this increase becomes comprehensible: By selecting very sharply over several steps, it was possible to fix lines, which proved to be much more productive (Fig. 18).



Biogas Production and Energy Crops. Figure 17

Dry matter yield (DM in t/ha) as a function of the maturity of the entire plant (DM% of 90 new energy maize hybrids (and 10 standards) from German–Mexican energy maize inbred lines, crossed with a German flint single. Reference SM - Silage maize for fodder production; Reference EM - Potentiale “Energy Maize” - Breeds showing higher yeild potential



Biogas Production and Energy Crops. Figure 18

New German–Mexican energy maize inbred lines (in each picture on the left side) next to conventional silage maize lines

It should be taken into account that this enormous increase in yield was achieved by improving just the genetics of the female parents of the experimental crossings. Therefore, those short-day genes should be used on the pollinizer side as well to increase the biomass potential of energy maize hybrids even more.

Outlook The outlined results demonstrate that different breeding strategies with very varied breeding material groups allow to realize enormous progresses in biomass performance and therefore in energy output of maize as an example crop. The results achieved up to now are considerably higher than expected.

The next goal of the energy maize breeding program is already defined: The considerable progresses in breeding, which could be generated up to now in the different breeding material groups, have to be united in the basic populations on which reciprocal recurrent selection is based, as well as in the hybrids. The breeding goal mentioned first (i.e., improving the total dry matter yield of maize in Central European temperate climate and stabilize it above 35 t/ha) will be reached within a short term.

The other energy plant species like sorghum, sunflower, or sugar beet have their specific breeding programs to combine most diverse genetic material to improve mass production. Energy plant breeding programs thus significantly differ from already existing standard breeding programs, as they focus on other breeding goals like energy efficiency and energy yield per hectare.

Cropping Systems

The decision on how to design cropping systems, and especially on which crop to choose, is based on the farmers' expectation of the economic gain from a specific production alternative. Apart from the natural yield capacity of a site and the revenues that can be achieved, this is determined by the crops' integration into agro-technology systems and the work organization. Importantly, the cropping structure is influenced by the existence of value-adding production capacities. These also include the biogas production.

Crop Rotation Design Rotation of crops is a basic element of crop production. The term rotation refers to the temporal follow-up of crops on one site. At the same time, the spatial juxtaposition of crops in a specific region is of special interest. Both aspects have a major influence on biodiversity, erosion by wind and water, and the appraisal of landscape characteristics; additionally, they directly influence aspects relevant to production. Extended or wide crop rotations, meaning crop rotations including a spectrum of different crops, for example, have the advantage of an increased utilization of water and nutrition reserves as well as the diminishment of weeds and pest biota.

A significant improvement of regulation possibilities, meaning the availability of plant protection products and mineral fertilizers, has led to a reduced economic importance of crop rotation design during the last century. Presently, control of nutrient supply by mineral fertilizers allows for the stabilization of yields. Yield breakdown caused by weed or pest biota can be prevented by plant protection measures. This, in combination with the tendency for specialization on a farm-scale as well as regional level has led to a narrowing of crop rotations. Presently, in Central Europe crop rotations including a high share of leaf fruits (i.e., potato, sugar beet) of 25–33% are only left common in the vicinity of starch or sugar plants.

On better production sites, cropping concentrates on winter wheat, winter rape, grain maize, and barley. In areas with best conditions for cereal production, the share of wheat can take up to 70% of the arable land, which implies a frequent self-succession of this crop. On less favorable sites, cropping concentrates on barley and rye. In regions with a concentration of livestock production, cropping concentrates on maize and barley; this – in the case of maize – can lead to a monoculture on some sites.

Energy plants can intensify this trend, for example, by extending the cropping of silage maize in livestock production areas. On the other hand, the cropping of plants that have little or no share in regional cropping systems can lead to an extension of rotations. Under present conditions, this can still imply free bonus effects, for example, cost reduction possibilities (e.g., plant protection or mineral fertilizers) or yield effects. Concerning winter wheat, depending on the fertilizing regime, the plant protection intensity and preceding

crop, yield increases of 10–50% can be achieved in comparison to a self-progression [73]. Providing for shares of sugar beet in the crop rotation can accordingly account for yield effects of 17% [74].

Furthermore, possibilities are given to productively use crops in the biogas plant, originally included into crop rotations for other reasons. Examples are the utilization of clover grass, which is primarily grown for nitrogen fixation on biological farms, or the combination of protective erosion measures by means of intercrops for their energetic use. As an overview and extension of the possible crops mentioned above, Fig. 19 shows possible options for energy cropping for anaerobic digestion and their rotational position.

Systems, which are based on the cropping of annual single main crops, either summer or winter crops, are of highest relevance in temperate climates. For energetic purposes, the cropping of a main crop is currently also tested in mixtures of species or breeds.

By adding intercrops, the vegetation time not used by the main crop can be utilized, for example, to increase annual yields for substrate production. Figure 20a and b show schematically the yield development process of winter and summer main crops with regard to solar radiation. Included into the Figure is the combination with intercrops.

Based on the approach of changing the cultivation span of the crops by shifting harvesting and sowing dates the so-called double-cropping system, including two equally productive crops, was proposed [75]. During the last years it was discussed if and on which sites a yield increase can be achieved. At the same time granting ecological advance, is one of the aims pursued by the system set-up (Fig. 20c).

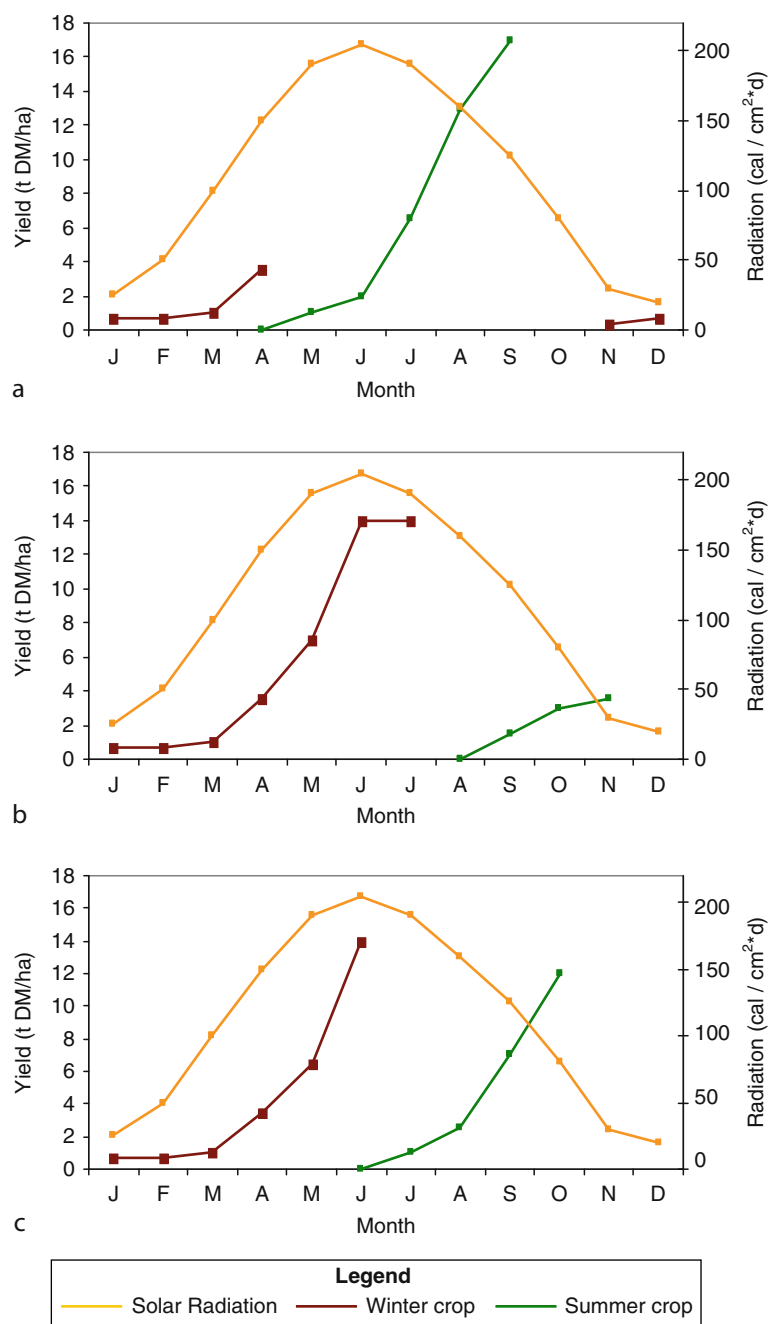
As shown in Fig. 21, various combinations exist to combine winter and summer crops. The possible time span for the change between winter and summer crop is flexible, depending on the choice of crop and the harvest stage. All in all, the time span for two crops providing similar yield amounts as shown in Fig. 20c covers a transition period of approximately 30 days. If winter intercrop and second crop (Fig. 20b) are also taken into account, the time span covers approximately 60 days.

Criteria for the possibility of yield increase by using these systems are the availability of water and the duration of the vegetation span. On soils with low field capacity, winter crops use the water reserve of the soil in spring, so without sufficient precipitation in the following period, risks for the establishment of the second crop rise. Still, even in the case of establishment success, lower water availability might reduce the yield of the summer crop, so combined yield might not be higher than the use of a single crop. On sites that

Single main crop		Double – cropping system/ Winter intercrop + second crop (including mixtures)		Perennial crops	
One crop	mixed cropping				
Sugar beet	Mixed cropping of species	Winter (inter-)crop	Second crop	< 4 years	≥ 4 years
Cereal (grain)	Maize + Sunflower	Winter rye	Maize	Clover/Grass	Cup plant
Maize	Whole plant cereals	Winter rye + w. vetch	Sweet sorghum	Alfalfa/Grass	Sida hermaphrodita
Whole plant cereal	Maize+ White sweet clover	Hairy vetch	Sorghum-Sudangrass	Grass mixture	Rumex
Sweet Sorghum	Maize + Sorghum	+ crimson clover	Summer rape	Jer. Artichoke	Polygonum
Sorghum-sudangrass	Whole plant cereal + winter pea	+ ann. Ryegrass	Sunflower		(Switchgrass)
		Grass mixture	Mustard		(Miscanthus)
		Clover/Grass mixture	Ryegrass/Grass mixture		
	Mixed cropping of breeds:	Winter pea			
	Whole plant cereals				
	Sorghum				
Green = traditional Orange = tested Red = new					

Biogas Production and Energy Crops. Figure 19

Optional positions of energy plants for anaerobic digestion in the cropping system



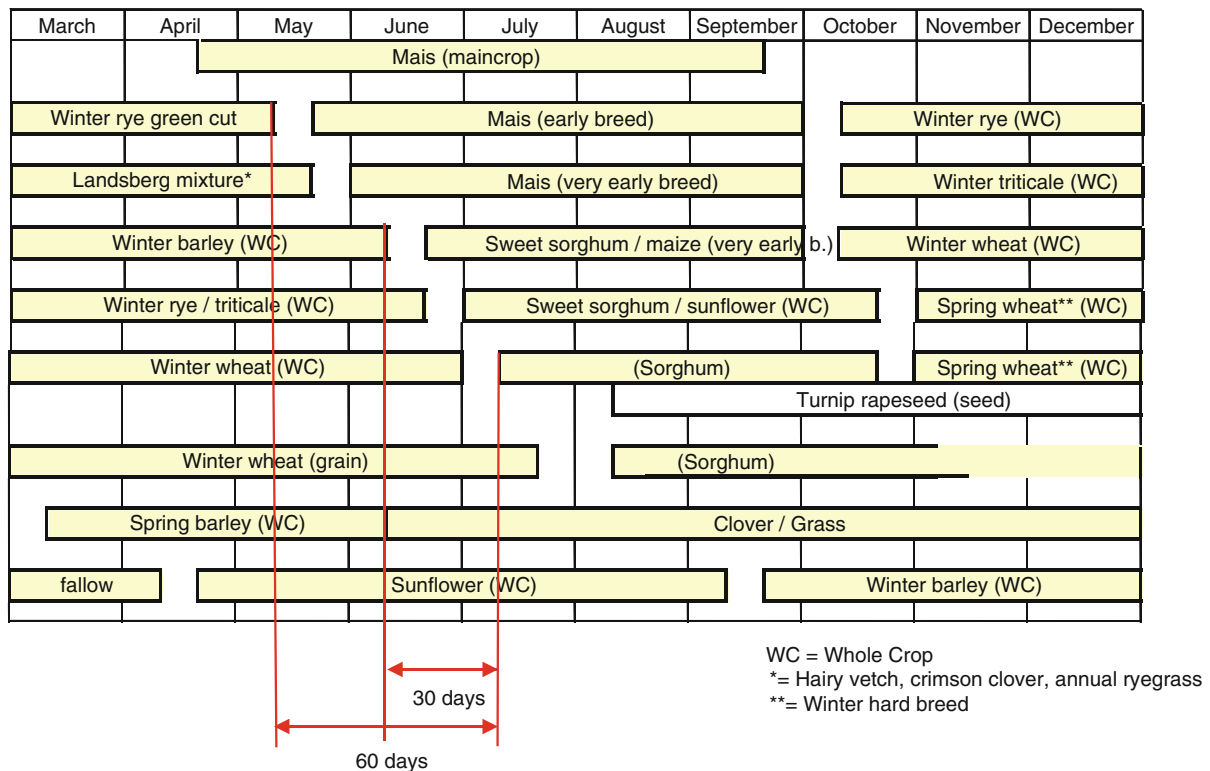
Biogas Production and Energy Crops. Figure 20

(a, b) Schematic yield development of winter and summer crop in combination with winter intercrop (*above*) and summer intercrop (*below*) (According to [75]). (c) Schematic yield development in the double-cropping system

show good water storage capacities (Quality wheat region, discussed later in the chapter) or sites with sandy soils but good precipitation amounts, by growing maize in combination with winter rye green

cut, a significant yield increase compared to maize as a sole crop can be achieved.

Also systems using late transition between winter and summer crop could provide surplus yields. In a 3-year



Biogas Production and Energy Crops. Figure 21
 Options for the utilization of two crops in one vegetation period

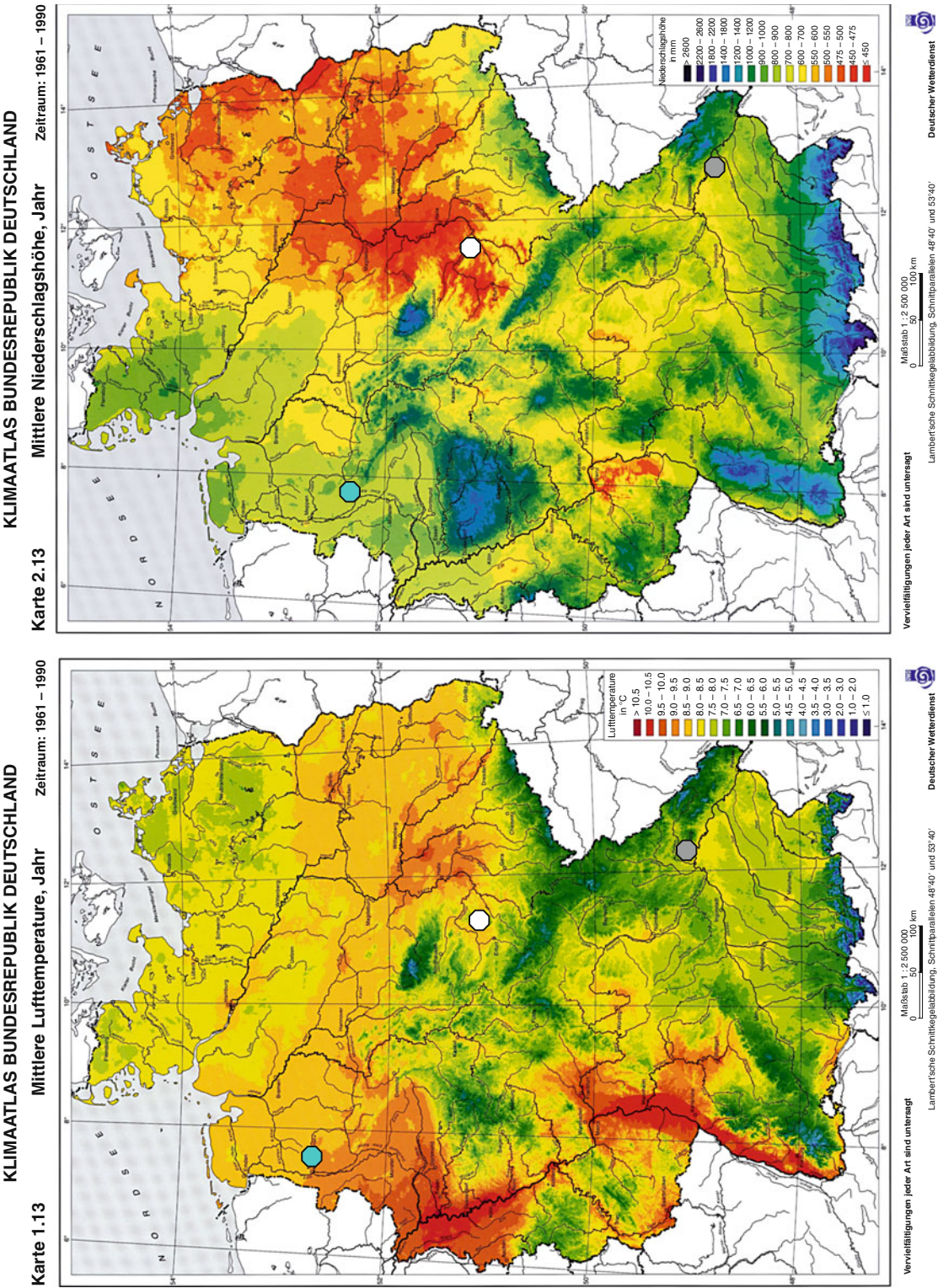
trial, a yield increase could be demonstrated for a range of different sites [76]. For the combination winter rye whole crop – maize, the comparative increase was 3.9 t DM/ha, whereas the variation in sites showed a variety of yield surplus of on average 1.9–5.8 t DM/(ha a) for a 3-year period. Under present conditions, the higher production cost for these systems in most cases exceeds benefits. For an evaluation, all free bonuses, starting from improved nutrient utilization due to all-year coverage of the soil, equalization of peak times, as well as improved ecological features should be taken into account. One of the central focus points to be set is the reaching of a sufficient dry matter yield for ensiling (see the section “[Harvest, Transport and Storage](#)”) by the second crop. An adapted choice of breeds can provide some leeway.

Regional Examples for Adapted Crop Rotations

Quality Wheat Region The quality wheat region (Fig. 22) is characterized by fairly low temperatures

(mostly 500–600 mm) and loess soils with high field capacity. Conditions are good to produce medium to high yields of quality wheat with high protein content. Within the region, livestock production is low and the share of wheat in cropping systems is very high. As a typical crop rotation, winter wheat – winter wheat – winter or spring barley – winter turnip rape can be pointed out.

Starting from this, winter cereal whole crops, for example, winter triticale can be included. Although shares of this crop are low, the yield expectations characterized are high. Exemplarily, the combination winter wheat – winter triticale WC – winter turnip rape is suitable for regional conditions. In addition, it is a cropping alternative, from an economic point of view, to the relatively unattractive winter barley. The yielding of whole-crop cereals or green-cut cereals in regions with extensive cereal cropping can also be regarded as an option to cut weeds with the crop



Biogas Production and Energy Crops. Figure 22
Annual precipitation (left) and annual temperature (right) in Germany as long-term mean (1961–1990) [77]

before the seed ripens and spreads. In this context, a significant decrease in focal weeds of plant protection has been shown [78]. A further possibility of crop rotation design for sites with a good availability of water in spring can be seen in:

winter wheat – winter rye green cut – maize
– winter wheat – sugar beet – maize

Instead of maize, for diversification and risk reduction, the cropping of sorghum is possible, too. Another option is the exchange of winter rye green cut for winter barley as a whole crop. Risks in the late establishment of maize have to be considered though. Additionally, the ripening of the summer crop as well as the trafficability of the field for the sowing of wheat should be considered.

Forage Cropping: Livestock Production Region This region of northwestern Germany (Fig. 23) is characterized by sandy soils. The maritime influence and the evenly distributed precipitation of an annual mean of more than 700 mm make good yields possible. The region is characterized by intensive livestock production and respective fodder production. The utilization of large amounts of manure for anaerobic digestion is advantageous; the problem of nutrient surplus will not be solved by anaerobic digestion though.

Due to a further increasing maize cultivation area for the purpose of biogas production in addition to fodder cropping, there is a further increased availability of nutrients; approaches focus on the increased combination of maize with intercrops. The breaking up of maize-based crop rotation, for example, by

Winter barley WC – maize – winter rye green cut – maize

can offer possibilities for increasing yields and serve further purposes such as nutrient leakage reduction and erosion mitigation due to a prolonged utilization period. Nutrient surplus in phosphorous balances in many cases limit possibilities for the utilization of fermentation residues. Therefore, approaches for the separation of fermentation

residues are currently being discussed. A much higher dry matter and phosphorous content in the solid phase allows for comparably good transportability, which makes export to sites with phosphorous demand possible. From a sustainability point of view, the decreased humus reproduction of the lacking solid phase has to be considered. From this perspective, ryegrass (mixtures) is mentioned as an alternative for the prevention of humus balance deficits and proves to be productive.

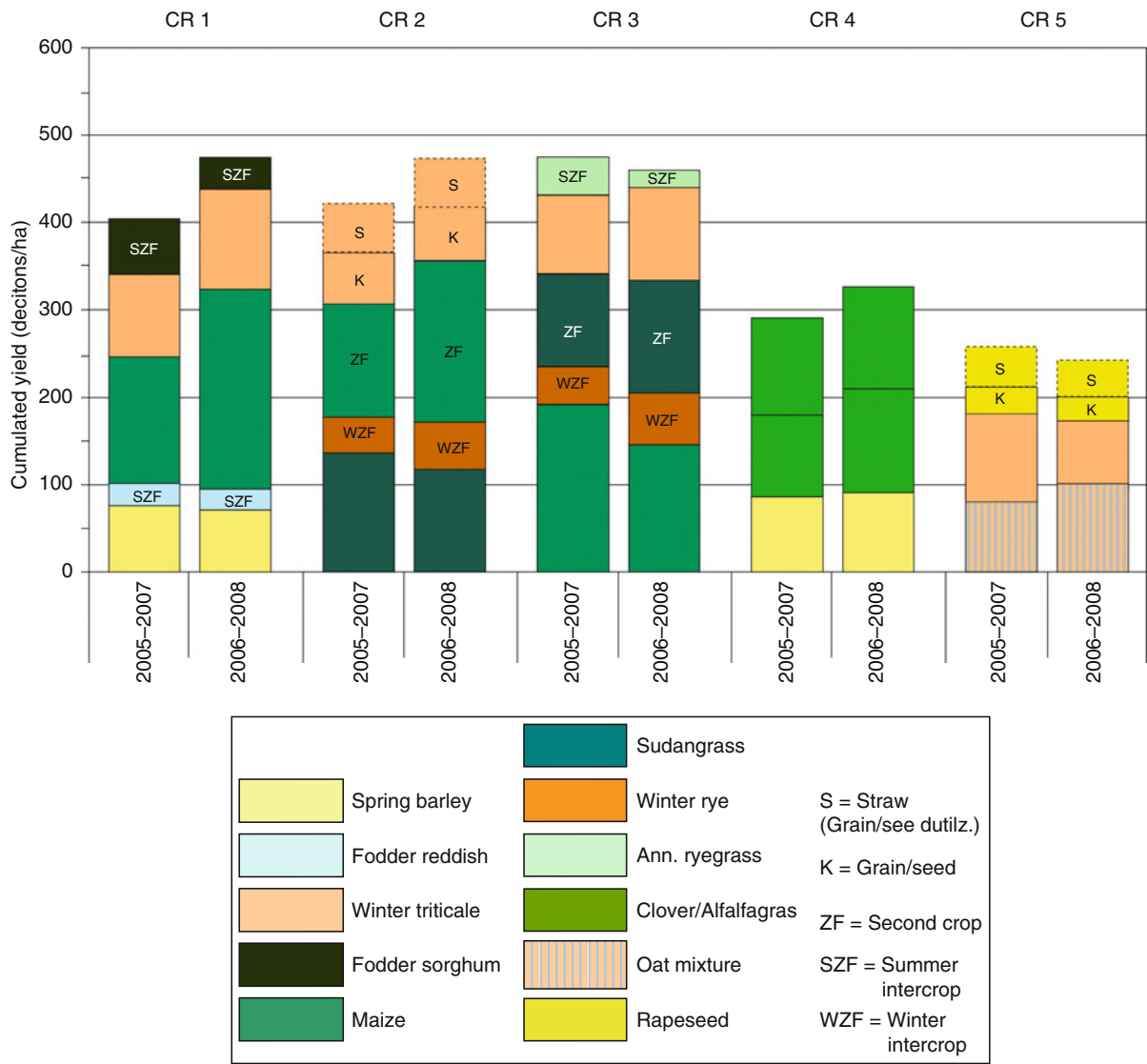
Forage grasslands – winter barley – region of German foothills and uplands

Large parts of Germany may be characterized as foothills and upland area. The conditions are, depending on altitude, relatively cool and moist. Soils are shallower and the relief is sloped. Lower temperatures make the cultivation of crops with high temperature demand or less winter hardness more difficult. Winter turnip, rape, and sugar beet are not suitable for higher regions. Maize has some importance on the more favorable foothill sites of Southern Germany. Of all the cereals, winter barley is the most important. One possibility for crop rotation design can be seen in:

Winter barley (grain) – winter triticale whole crop
– spring barley + underseed clover grass
– clover grass 2nd year – clover grass 3rd year

On farms with livestock production or possibilities for the sale of fodder, utilization of clover grass for both biogas and cattle fodder is a possible option. Hence, systems can be based on the fact that due to differing substrate demands, a (relatively observed) higher usability of the late cuts in the biogas plant can be pointed out. This is based on the higher risk of the higher contents of acetic acid, which does not, in comparison to cattle fodder production, pose a quality issue in biogas substrates.

For the design of varied crop rotations with high shares of energy plants, different crop rotations were tested in plot experiments on seven sites in various agricultural regions in Germany as part of a large cooperative project since 2005. The aim of the project is to



Biogas Production and Energy Crops. Figure 23

Cumulated yields of the uniformly tested crop rotations as a mean of all sites for the first (2005–2008) and second (2006–2009) plot set (CR = Crop rotation) [79]

evaluate which crop rotations are preferable from an economic, ecological, and plant-production point of view. On the different sites, five uniform and three to four regionally specific crop rotations were tested from 2005 to 2008 and shifted by 1 year from 2006 to 2009. Figure 23 exhibits a general overview of the mean yields on all sites of the five uniform crop rotations.

Crop rotation number 3 (maize – winter rye (green cut) – Sudan grass – whole crop winter triticale – annual ryegrass) was the most productive crop rotations on many of the sites, despite yield variations ranging from 33.6 to 56.7 t DM/ha. Sites in the regions described above could in general provide very good results. On the site of the quality wheat region, the cropping of Jerusalem artichoke and crop rotation

number 2 (Sudan grass – winter rye (green cut) – maize – winter triticale (grain usage)) could produce the highest yields, which were higher than those of a maize-monoculture. On the site representative to the forage grasslands – winter barley – region of German foothills in Ascha, relatively high yields could be provided, using a crop rotation consisting of maize – winter rye green cut – maize – winter rye/w. vetch mixture – Sorghum – Sudan grass. An explanatory approach for the high yield of this crop rotation, which is rather untypical of elevated sites, is in comparison, the higher long-term mean temperature during the experimental years with a sufficient water supply. On the site of the *forage cropping livestock production region* (Werlte), a 3-year combination of winter rye green cut and maize had a significant advantage compared to other options.

In total, the advantage of maize as a biogas substrate under a large spectrum of conditions in Central Europe could be confirmed. By also confirming the high yields of other substrates such as whole-crop cereals, sorghum, legume-grass, or grass mixtures (which can be taken into consideration in crop rotation design), complementarities could be pointed out [49].

Excursus: Factor Intensity with a Focus on Plant Protection Aspects With regard to the design of cropping systems for energy plants, altering the cropping intensity to contribute to an optimization of production systems has been discussed. On the one hand, this was related to the reduction in intensity of cropping systems by maintaining yield levels. On the other hand, questions dealt with a significant increase in yields by increasing the cropping intensity and at the same time considering sustainability issues.

Besides the above-mentioned considerations on double-cropping systems, one example for the latter is the irrigation of energy crops. In a 3-year trial, it has been pointed out that irrigation is suitable for securing a high yield level [80]. At the same time, a prognosticated climate change toward dry/hot summers and moist/mild winters in Central Europe could lead to a higher need for irrigation during summer months. Apart from the yield increase and the level of product price and the cost of irrigation, risk considerations are to be taken into account when

deciding if, where and to what extent irrigation should be implemented.

Examples for a reduction of intensity levels which can be mentioned include a reduction in cutting frequency within cultivation systems of multi-cut perennial forage mixtures, reduced tillage intensity [49], or the design of cropping systems with regard to aspects concerning factor input reduction (plant protection or fertilizer management).

In the production of whole-crop cereals, different quality requirements compared to the production of baking cereals make quality-oriented nitrogen applications for increased protein contents dispensable. A reduction in fertilizer levels below withdrawal values is noticeable much quicker than in maize though. On sites with a sufficient supply of organic nitrogen stock, maize can show better results as times of high mineralization concur with times of high nitrogen demand. In a mid-term view, a yield reduction in any crop cannot be avoided if fertilizer application is reduced below withdrawal values.

Likewise, minimal reduction possibilities can be pointed out for the reduction of plant protection measures in maize cropping in comparison to existing cropping systems. Weed control for example, is indispensable due to slow youth development of the plant. However, given the very high cropping share of maize in crop rotations and regional cropping structures the risk of problematic weeds increases (such as Crane's Bill (*Geranium L.*)). Additionally, the risk of an increased appearance of the European corn borer (*Ostrinia nubilalis*), and in some regions the Western corn rootworm (*Diabrotica virgifera*), has to be mentioned as this can lead to an increased necessity for plant protection measures.

Whole-crop cereals differ from cereals harvested for grain purpose with regard to the cropping span. Risks of ear infection, pest biota, and weed problems are therefore comparatively lower. Depending on the type of cereal, breed and site characteristics, and yield expectancy accordingly, plant stability may be sufficient to dispense with growth regulators. This is the case primarily on dry and low-yielding sites and for winter triticale and winter barley. On productive sites, growth regulators should not be dispensed with. Turning down fungicides can result in a decrease in yield. Under the

conditions of the quality wheat region, in most cases, reduced benefits are lower than the economic cost for treatment [81]. On sites with low weed pressure, the comparatively high competitive strength of whole plant cereals can provide possibilities for the reduction of herbicide measures.

In a broader perspective on entire farming systems, anaerobic digestion may also provide possibilities to utilize lots for conventional grain/seed production with heavy pest or weed infestation in biogas plants. Importantly, it was questionable if pest biota or weed seeds can outlast the biogas process and lead to higher infection/weed pressures when recirculating fermentation residues to the field.

According to [82], preliminary results are available for 14 phytopathogens involving relevant quarantine diseases of potato. Following these results, most pathogens cannot persist in digesters working in mesophilic conditions under common retention times. Only *Clavibacter michiganensis* subsp. *sepedonicus* shows a viability of more than 100 days. When supplying entire potato tubers, *Ralstonia solanacearum* could persist for 30 days in a batch experiment. According to this, a retention time span from practical biogas plants could be sufficient to provide the required sanitizing environment. *Xantomonas translucens* pv. *graminis* survived the process for 26 days. After 6 days however, infectiousness stopped. Additionally, it should be pointed out that ensiling might already kill pathogens before anaerobic digestion.

Of high relevance for intensive cereal cropping regions is the statement that the decomposition of *Fusarium graminearum* could be observed after 1 day [82]. This confirms results from [83], which, in addition, point out the disintegration of mycotoxins.

Survival of the seeds of some weed species is possible and continues to be the focus of research activities. One of the key parameters appears to be the temperature level of the biogas plant. In thermophilic conditions, seeds of blackgrass (*Alopecurus myosuroides*), goosefoot (*Chenopodium album*), stinkweed (*Thlaspi arvense*), broad-leaved dock (*Rumex obtusifolius*), and wild mustard (*Sinapis arvensis*) lose their ability to germinate after a retention time of 24 h. In mesophilic conditions, this only applies to blackgrass and wild mustard. Goosefoot had a germination ability of 75%. The durability of the testa against microorganisms could

play a major role. Seeds of goosefoot, black-bindweed (*Polygonum convolvulus*), and cockspur (*Echinochloa crus-galli*), which proved to be unable to germinate on agar, were still found to be viable in a Tetrazolium test [84]. Further results on the topic are awaited.

Harvest, Transport, and Storage

The bridging of the spatiotemporal difference between yielding of the crop at the optimum time on the field and the feedstock requirements in the digester make an optimized planning of harvesting procedure, transport, and storage of a specific substrate necessary. The specific challenges of supplying sugar beet are described in the section “[Production Systems of Sugar Beet](#)”.

Harvest and Transport Harvest date of the chosen crop type and breed is primarily oriented according to the maximum yield and substrate quality, but also according to the inclusion into crop rotations and work organization of the farming company. With regard to these factors, time frames for harvesting are determined for the different crops.

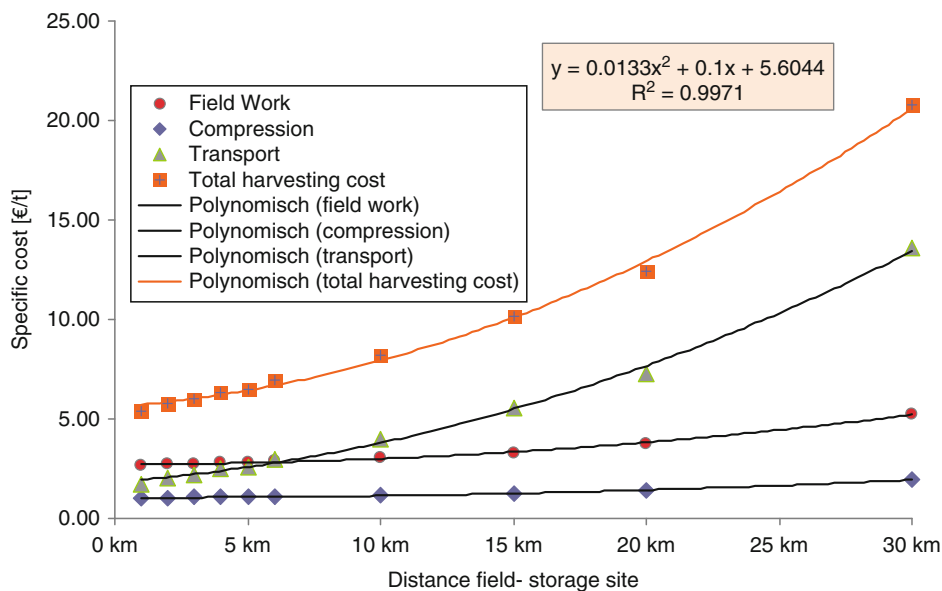
Most crops can reach the dry matter contents necessary for ensiling (see below), so harvest procedure can be single-stepped. For Grasses and green-cut cereals with low dry matter contents, the cutting can be done as a separate step, after which a phase of wilting is followed up, needing a period of 1–2 days of suitable weather conditions. When reaching optimum dry matter contents, swathed material is picked up by a chopper. Compared to sufficiently dry substrates, which are directly harvested, additional losses have to be calculated with.

Standard operation system for harvest and transport is the chopping chain. A central element is the utilization of a self-propelled forage harvester; to some extent is also that of tractor-mounted choppers. Capacities of forage harvesters sold on the market are in the range of up to 1,000 HP effective output. Depending on the substrate to be harvested/picked up, harvesters can be fitted with different harvesting units. One of the most important parameters for an economic operation is the throughput rate (Harvested Mass times Working Speed). In the forage harvesters currently available, depending on the installed engine

power, this can be equal to up to 300 t of fresh matter per hour.

For an optimized anaerobic digestion, chopping size is an important parameter. In batch tests, maize, which was chopped to an average size of 4.7–5.4 mm showed 8% higher methane yields per t DM than maize with average chopping sizes of 7.9–9.9 mm [85]. With increased lignification, finer chopping, which can be characterized as mechanical pretreatment, makes an even higher percentage of methane yield increase probable [85–87]. Short chopping sizes lead to a loss of efficiency and higher diesel demand during chopping operation – therefore an economic optimum is to be aimed for. For an efficient design of operation procedures, a continuous transport from the field is to be vouched for. Most commonly, a parallel operation procedure is used in which changing transport units (consisting of tractor and transport hanger) move besides the harvesting unit and transport the feedstock to the silo. The loading mass is influenced by the bulk density of the substrate. Even with an optimized design of the operation procedure, cost is significantly increasing with transport distance. The cost increases disproportionately (Fig. 24) [88, 89]. Low dry matter contents also have an effect on transport cost per dry matter (and energy yielded).

Storage To ensure continuous feeding of the plant with seasonally harvested material, the process of ensiling is used. For this, the substrate is compacted, with the goal of appropriately excluding air to ensure that the lactic acid fermentation process is optimized. In this type of fermentation, carbohydrates from plant material are converted into acids, which have a conserving influence. The conversion processes of ensiling involve an unavoidable loss of energy and matter. The overall losses, which might also involve noxious fermentation, seepage sap losses, and aerobic deterioration during storage and withdrawal, can be minimized, though [90]. The specific challenges in conserving root and tuber substrates which show little ensiling quality is dealt with exemplarily in the section “Sugar Beet”. A high share of usable carbohydrates and a sufficient number of suitable microorganisms on the plant material has a positive influence on the process. A high share of proteins and minerals (buffer) leads to the bonding of acids, which reduces the ability to lower pH-values. The deciding criterion for the design of cropping systems is the achievement of dry matter contents favorable for ensiling processes. Depending on the substrate type, values of at least 28% should be aimed at. Substrates significantly lower in dry matter content have a lower



Biogas Production and Energy Crops. Figure 24

Specific harvesting cost of maize from a 5 ha-plot as a function of transport distance [88, 89]

suitability for ensiling and depending on the height of the substrate in the silo, big quantities of seepage sap can leak from the silo. These quantities are to be used in the biogas plant. Dry material (>35% dry matter content) is much harder to be compacted, so risks for large losses from aerobic deterioration are increasing. With regard to overall losses in this step of the process due to insufficient ensiling qualities, up to 31% decreased methane yield in comparison to laboratory-scale ensiling has been found [91].

Losses that occur in form of carbon dioxide, hydrogen, nitrogen oxides, or ammonia are unavoidable though. The inevitable losses by final respiration processes and the activity of fermentation organisms are at least 5% of the net energy in the plant material [21]. In addition, losses occur by incomplete exclusion of air in boundary areas and aerobic conditions at times of withdrawing the substrate. Additional losses of at least 3% of the net energy can be expected. Biological or chemical silage additives can be added to the substrate to avoid large silage losses. It should be noted that by using biological silage additives, which are based on homo- and heterofermentative lactic acid bacteria, an increased amount of acetic acid might be formed [92]. While this is a negative aspect for the quality assessment of silages used for fodder, in the process of biogas formation, acetic acid has no negative influence.

Considering the requirements for a loss-minimizing ensiling process, the silages can be stored for a longer period of time [93]. Despite the higher cost for storage space, this gives leeway for substrate provision. In laboratory-scale experiments, losses of silages stored for 365 days were increased by 1.2–6.4%

compared to silages with a short storage period. The tendency of increased gas formation potential of the longer stored silages could compensate for the losses though.

Utilization of Fermentation Residues

Production systems for anaerobic digestion are specifically characterized by the fact that fermentation residues can be recirculated as organic fertilizer. After the digestion process in the plant as shown in Fig. 8, barely digestible substances are still in their original structure. Substance groups with good digestibility are largely mineralized to soluble inorganic compounds.

Due to the fact that only little substance losses occur (e.g., in the process of ensiling, see above), and that nutrients in the residues are – in comparison to those in feedstock before digestion – by far more available to plant uptake, biogas systems are suitable to design largely closed nutrient cycles.

A factor in the evaluation of nutrient cycles, which also has to be taken into account, is that only few biogas plants only use plant material for digestion. In fact, anaerobic digestion is very suitable to utilize excreta from animal production. Mass flows, which in many cases include nutrient input by imported fodder, also have to be taken into account.

Analysis of the fermentation of different biogas plants fed with dedicated energy crops and carried out at different times show the large variety of nutrient levels (dependent on substrate input, pretreatment, and digestion rates) in fermentation residues (Table 4).

Biogas Production and Energy Crops. Table 4 Dry matter and nutrient contents as well as pH values of fermentation residues exemplarily in central (Thuringia) and south-western Germany (Baden-Württemberg) [93, 94]

		TM%	pH	N _{ges}	NH ₄ -N	P ₂ O ₅	K ₂ O	MgO	CaO	S
Baden-Württemberg N = 102	Mean	7.0	8.3	4.7	2.7	1.8	5.0	0.84	2.1	0.33
	80%-qrtl.	5.0	7.9	3.9	2.1	1.2	3.8	0.47	1.5	0.26
	20% qrtl.	8.5	8.6	5.5	3.3	2.1	5.5	1.04	2.6	0.41
Thüringen N = 60	Mean	5.8	7.7	4.2	3.1	1.8	3.4	n.v.	n.v.	0.04

Compared to animal manure, the relatively close relation of C/N in fermentation residues is to be mentioned. This leads to a decreased immobilization of the nitrogen included in the fermentation residues [95]. Due to the comparably high contents of ammonium, nitrogen is also present in a form well available for plant growth. Depending on the crop type, recommendations are to calculate 60–80% of the total nitrogen in the fermentation residues as equivalent to mineral fertilizer [94, 97]. In summer crops, in comparison to winter crops, higher percentages can be taken into account. Values for mineral fertilizer equivalents of 77% for maize and 86% for spring wheat have been shown [96]. Phosphorous and potassium can almost completely be recycled [97].

The release of calcium in anaerobic digestion leads to higher pH-values compared to animal manure, which is not utilized in biogas processes. Whether higher values for ammonia emissions occur, is in discussion. Fermentation residues have a relatively low viscosity, which leads to better handling (homogenization, pumpability, etc.) and soil-infiltration properties. This leads to the fact that the higher emission risk due to increased pH-values can be compensated for [96]. In any case, loss-minimizing technologies as well as an immediate incorporation into the soil are means of avoiding ammonia losses. These can be minimized, but not completely eliminated.

The usability of a relatively good fertilizer and a saving of mineral fertilizers (in comparison to grain/seed production systems) have to be considered when evaluating biogas systems. It should also be noted that in regions with high nutrient input by fodder imports and an increased cycling of nutrients, nutrient balances, for example, of phosphorous, can be limiting due to maxima set by legislation. Solutions, such as the separation of liquid and solid parts of the residue are currently under discussion. Different technical approaches to the separation have in common that both phases have a different nutrient content. The liquid phase is higher in NH_4 -content related to total N-content, but has a smaller phosphorous content. The solid phase can include up to 70% of total phosphorous. It is more transportable and can be exported into regions with a phosphorous demand [98].

From an economic and an ecological point of view, the utilization of nutrients in the fermentation residues should be in the most efficient manner. Rules of “good agricultural practice” as well as binding legal regulations are to be followed. These include:

- Limiting the fertilization span on times in which nutrients can be used by crops
- Knowledge of plant demand and nutrient contents of the fertilizer
- Limiting the quantities and area balances accordingly
- Specification on the storage of residues
- Specification of the loss-minimizing deployment technique
- Extended requirements in the utilization of waste material, for example, contagion hygiene requirements

Already during the planning phase of biogas plants, the management of fermentation residues should be involved. Especially in large plants, the low transportability of the fermentation residues should be considered. Optimized fertilizing strategies require efficient deployment logistics, especially in times where deployment makes a maximum uptake of nutrients by plant growth possible.

Sustainability Aspects

For a long time, sustainable management has been a basic principle of agricultural production. As part of this production, the cultivation of dedicated energy crops is therefore underlying the rules and guiding principles of “good agricultural practice” in addition to Cross Compliance requirements and further regulatory and prohibitive instruments. The increased production of dedicated energy crops and the associated support programs were linked to public institutions formulating further goals that aim at an increased contribution of energy cropping toward a sustainable design of energy and land use systems. Central aims are to contribute to greenhouse gas mitigation and environmental protection, as well as saving fossil fuels and decreasing the cost of energy supply also with regard to external costs and technology development [3]. Furthermore political aims are targeted at safeguarding the energy supply, preserving

biodiversity and soil fertility, and contributing to employment and value creation especially in rural areas [99].

Depending on the weighting of the different target values, differing assertions and deductions toward the design of agricultural systems can be drawn. Additionally aggravating is the fact, that quantitative and comparable evaluation categories can sometimes be barely defined and controlled for a number of targets. Accordingly, for the quantitative approach of life cycle assessment, in addition to the definition of a reasonable “balance scope,” for the evaluation of target values, a subjective value system has to be referred to [100].

Green House Gas Balance

Based on the fixation of carbon dioxide by photosynthetic processes and the utilization of the fixed carbon to substitute fossil fuels, agricultural production can contribute to climate gas mitigation. Furthermore, the anaerobic digestion of excrements can also contribute to the reduction of emissions caused by other fields of agricultural production. To estimate to what extent the utilization of dedicated energy crops can contribute to a mitigation of climate gas emissions, the net climate gas reduction is to be calculated. Basically, this is determined by the balance of reduced emissions due to substituted fossil energy sources and the sum of emissions in the production system.

Emissions in the production system are not only determined by the factor input (fuel and fertilizer production) for cultivation steps, but also by climate gases emitted in substance cycles such as methane and nitrous oxide. Influence on the emission of methane is provided by mitigation potentials during the utilization of excrements. Otherwise, risks of methane emissions during the process of anaerobic digestion and utilization of the gas have to be mentioned. The largest emissions that are relevant to climate warming from soils are those of nitrogen compounds, which are linked to the utilization of mineral and organic nitrogen fertilizers.

For the evaluation of climate gas mitigation in the cultivation of renewable raw materials, a range of values can be looked at. Apart from the overall emissions that are avoided by the substitution of fossil fuels by biogas, these are mainly evaluation values for a specified area

(kg CO₂-eq/ha) or product quantity (kg CO₂/GJ) as well as the associated cost. Furthermore, when looking at evaluation values, the subdivision into avoidable and unavoidable emissions is helpful.

Output and Substitution Values Decisive values for energy and climate gas balances are the methane yields of the different crops and crop rotations per unit of area. High hectare yields provide the possibility to substitute high amounts of fossil fuels. Relative indices, which give (energy) input in relation to output, often have the weakness of not considering the area as the scarcest factor.

Extensive production can lead to a reduction of energy-related factor usage and emissions. However, a thorough risk evaluation should be done, when assessing minimization strategies as well. An extreme example can be seen in the waiving of plant protection measures in the cropping of maize – yield loss and the respectively lowered energy gain will overcompensate the reduction in energy input by several times [101].

For a further evaluation of greenhouse gas savings potential, the reference base for example, the emissions of the substituted energy also plays a major role. Highest greenhouse gas reduction potentials can to be seen in the substitution of electricity produced from coal (e.g., lignite). Against this assumption, assuming a flexible electricity production with biogas substituting natural gas-driven peak load power stations leads to lower greenhouse gas savings.

Primary and Secondary Emission Values Primarily relevant to greenhouse gas emissions are factor inputs for the working processes that are necessary for the establishment, fostering, and harvest of a crop. These are most importantly not only fuels, but also fertilizer and plant protection products. Energy- and material-related emission values for provision of machinery and maintenance should be accounted for as well.

Of high importance is the kind of tillage system used. Minimum-tillage-systems waiving the usage of plowing measures have an advantage because of less fuel demand. Furthermore, the distance of the field from the biogas plant is relevant, since large parts of the energy have to be used for transporting processes. Values for conventional

plowing systems and a transport distance of 6 km have been calculated. For a Thuringian site, for example, these add up to between 58.9 l/ha (sorghum) and 82.9 l/ha (maize) [102].

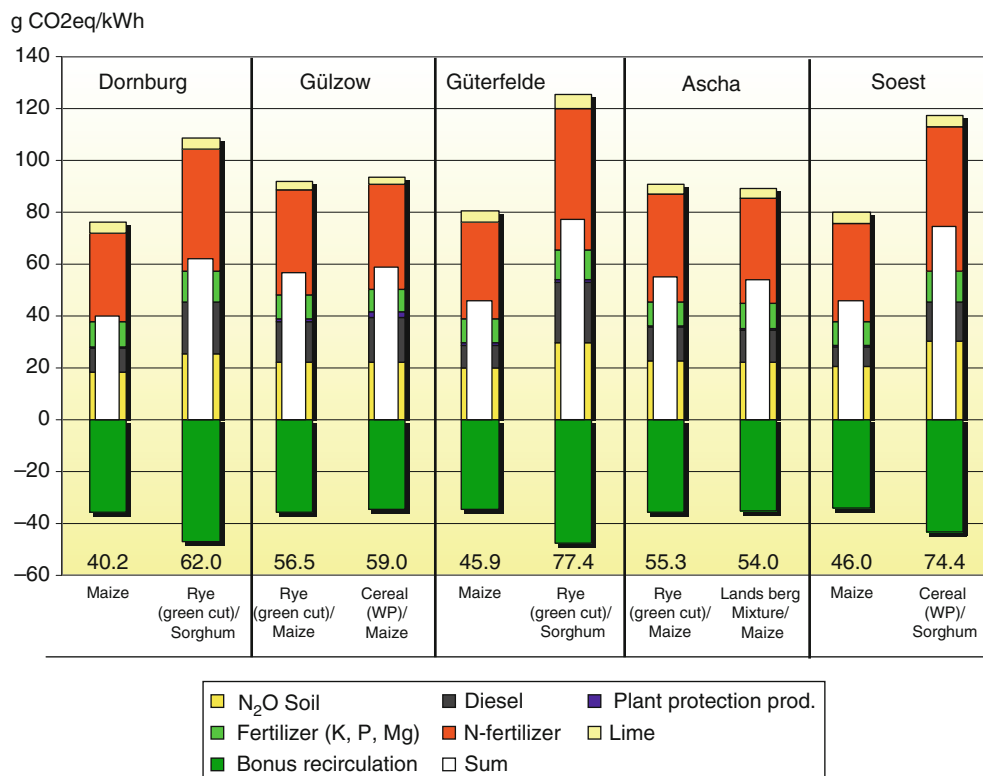
Fertilizing can be regarded as the quantitatively most relevant part of emissions. Firstly, this is due to the energy-intensive production of mineral fertilizers. Because of the possibility to efficiently recirculate nutrients in biogas production systems, in comparison to market crops bonuses (when used in other crops) or reduced mineral fertilizer input have to be taken into account, though.

Secondly, secondary emissions from production-related nutrient cycles have to be considered. Of high relevance are the emissions of nitrogen compounds (most importantly nitrous oxide) emitted in the course of nitrification and denitrification processes. The emissions of this gas are relatively small quantitatively; though with a high radiative forcing, they make up

a large part of climate gas emissions of intensive cropping systems.

Figure 25 shows the resulting climate gas emissions for the production of one kWh of methane that can be attributed to energy cropping systems on different sites in Germany.

Shown as white columns are the balances of emissions and bonuses which have been taken into account by the recirculation of residues (green). The relatively low values for maize can be explained by the good yield (and energy gain accordingly) in relation to the input and according emissions. The combination green-cut rye and sorghum on the dry and sandy site Güterfelde leads to the highest emissions, which can be explained by the relatively low yields at this site. With regard to the high share of emissions in the field of fertilizing, the nitrogen efficiency, and therefore, the nitrogen input per unit of product (in this case methane) is of outstanding importance. In this context, it should be



Biogas Production and Energy Crops. Figure 25

Resulting climate gas balances for different options of cropping of energy plants on different sites in Germany [102]

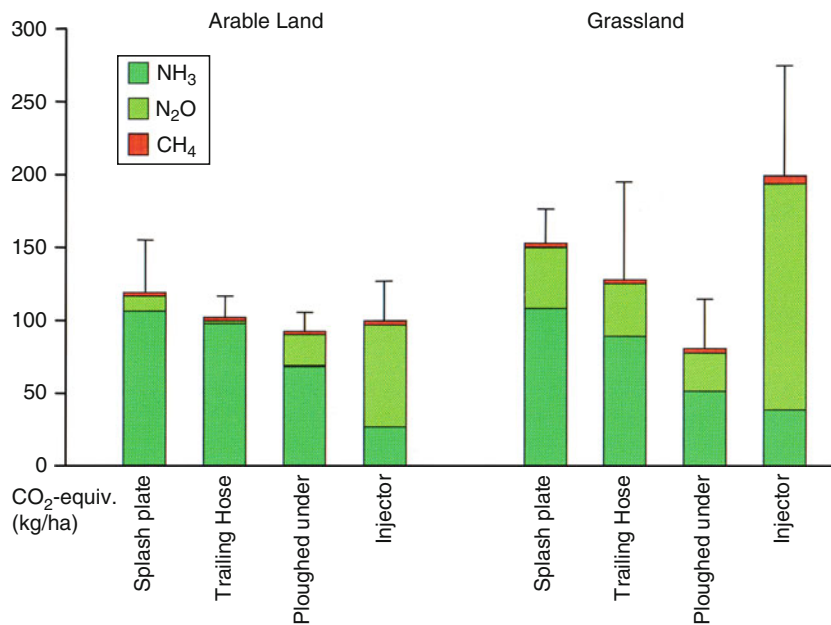
mentioned that the values used in Fig. 17 are calculated on the base of standard values proposed by IPCC, who recommend a calculation involving the emission of 1% of fertilized nitrogen as nitrous oxide.

For the specification of this simplified quantitative interrelation, as well as for the closer characterization of the “new” fertilizer fermentation residues, several research projects are currently ongoing. One thing that can already be stated is that the processes of nitrification and denitrification, which are the base of nitrous oxide emissions, are based on the insufficient utilization of nitrogen rather than the total amount of fertilized nitrogen [103]. Additionally, the availability of oxygen during the alteration processes of nitrogen compounds is of high relevance. On soils with high contents of clay and a nitrogen utilization of less than 30%, the emission of nitrous oxide is increasing disproportionally [104]; nitrous oxide emission also increases considerably on water-saturated soils emissions after organic fertilizing [105]. Furthermore, the frost–thaw cycles during winter seasons in temperate climates lead to large quantities of nitrous oxide emissions. These emissions are unavoidable, but can be

minimized by an optimized fertilizer application in spring and an optimized plant uptake before winter takes place. Influence on emissions of nitrous oxide and ammonia also can be taken by an optimized fertilizer application technology (Fig. 26).

From a technological point of view, the splash plate is obsolescent. Injector technology is largely avoiding ammonia emissions, but this leads to the highest emissions of nitrous oxide [107]. Ultimately, a target conflict between minimizing emissions of ammonia and nitrous oxide can be pointed out.

Clearly, nitrogen fertilizing should always aim at an optimized utilization within the entire system. An optimized adaptation of crop rotations under consideration of intercrops, in addition to the efficient inclusion of maize into market cereal crop rotations, can promote a more efficient usage of nitrogen within the farming system. As an example, for an extension of the crop rotation of a cereal-oriented farm by producing biogas and selling straw a clear reduction of overall nitrogen surplus is achieved [107]. This example also points out that not only is the reference system of substituted energy form, but the reference system of alternatively



Biogas Production and Energy Crops. Figure 26

Influence of spreading technique for fermentation residues on resulting emissions (Shown in CO₂-equivalents) [106]

stated usage of the arable land is of major importance for evaluation of ecological impacts.

In conclusion, on the field of optimized organic fertilizing with fermentation residues, there is still a demand for further research. From a practical agriculture standpoint, research should point out possibilities to optimize the utilization of nutrients in the fermentation residues; from a sustainability point of view, on the other side of that same coin, the minimization of nitrogen losses should be strived for.

Humus Balance and Preservation of Soil Fertility

As mentioned in the section “[Soil and Nutrient Supply](#)”, organic substances in agricultural soils play a major role for nutrient storage and transformation processes. Furthermore, on a global scale, organic substances in soil serve as an important carbon sink. Contents of carbon and humus are not identical, though. In most cases, the carbon content (C_t) multiplied by the factor 1.706 equals the humus content. In soils containing carbonate, the share of inorganic carbon has to additionally be taken into account.

The dynamic character of trans- and deformation processes of organic substances in soils makes it necessary to perpetually supply soils with organic matter, in the appropriate amount of the microbial disintegration to mineral substances, in order to sustain the level of soil organic matter content. Therefore disintegration rates are of interest. These are influenced by climate, nutrient supply, soil structure as well as the tillage system used.

Major sources of supply for organic substances are roots and harvest residues. Crops can accordingly be differentiated into humus-diminishing crops (e.g., sugar beet) or humus-increasing crops (e.g., perennial grasses). Furthermore, the supply of additional aboveground biomass such as straw and the recirculation of organic fertilizers are important sources for soil organic carbon.

In energy plant production, which aims at a utilization of total aboveground biomass, only little harvest residues are left on the field in comparison to, for example, the production of cereals for grain usage. By recirculating fermentation residues, large quantities

of carbon-rich substances, which could not be disintegrated in the process of anaerobic digestion, are resupplied to the soil, though.

Distinct changes in the humus content of soils can only be observed within longer periods of time. In this context, it should be noticed that depending on site characteristics and the chosen management system, only in the long-term specific humus content is materializing. To be able to evaluate these processes quantitatively, several models exist that provide reference values for humus formation and decomposition derived from long-term tests.

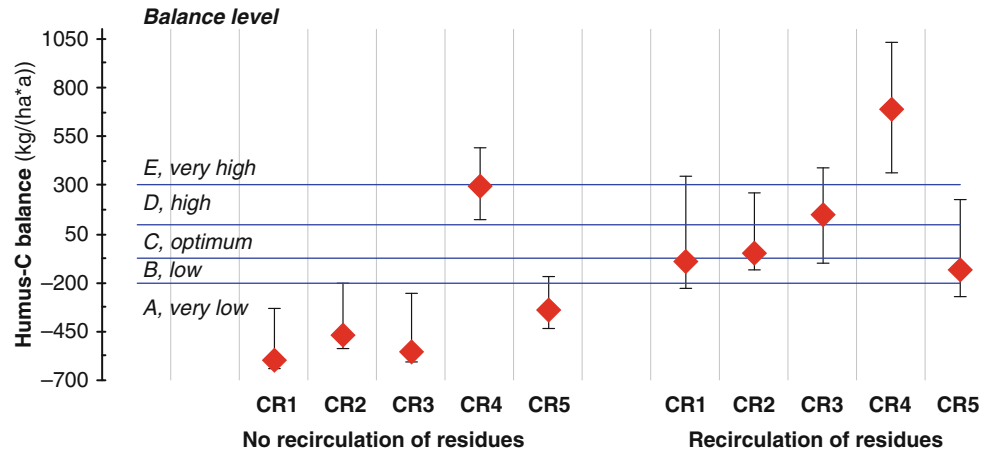
Such models are the VDLUFA-Method, the Repro-Method and the Site-adapted Balancing Method [108]. All methods differentiate between the cultivated crops. Exemplarily, the VDLUFA-Method exhibits an annual humus decomposition for maize of between 560 Humus-C ha⁻¹ (on soils showing a good state of cultivation with optimum mineral fertilizing) and 800 kg Humus-C ha⁻¹ (on soils which have been poorly supplied with humus for a longer time and soils under ecological management practices) (Table 5).

A calculation of humus balances of cropping systems for rotations including a high share of energy plants shows that except for the rotation which includes a perennial forage mixture, a cropping without recirculation of residues would lead to a decreasing humus content in soils and hence a decreasing soil fertility on Central European sites (for a description of the crop rotations see Fig. 24). This should be considered, for example, in concepts for fuel production (Biomass to Liquid, BtL) which, in contrast to biogas production, do not allow for a recirculation of residues which contribute to a supply of organic matter.

As can be seen on the right part of Fig. 27 a recirculation can lead to a much better supply of humus in the tested crop rotations, when considering the recirculation of residues. In crop rotations with a high share of perennial forage mixtures (CR 4), the recirculation of organic matter causes balances which bring about the risk of high and uncontrollable mineralization. For the calculation, a humus reproduction rate of 0.3 for the fermentation residues was estimated. The reproduction rate describes the

Biogas Production and Energy Crops. Table 5 Change of Humus-Carbon dependent on specific cropping in various energy crops ([109] according to data from the EVA-project)

Crop	DM-yield (tha ⁻¹)	Specific change of Humus-C	
		Dynamic HE-method [110, 111] (kg ha ⁻¹)	VDLUFA [112] Lower value to Upper value (kg ha ⁻¹)
Whole-crop cereal	8.1	−595	−280 to −400
Silage maize	17.6	−969	−560 to −800
Sorghum (bicolor × sudanense)	12.3	−609	
Sorghum (bicolor × bicolor)	9.0	−592	
Rye (green-cut intercrop)	4.8	87	120 to 160
Annual ryegrass (summer intercrop)	3.7	81	100 to 150
Clover/Alfalfa grass (Main utilization year)	10.9	829	600 to 800



Biogas Production and Energy Crops. Figure 27

Resulting humus balances of crop rotations with high shares of energy plants without including humus reproduction by recirculated residues (*left*) and with the inclusion of reproductive values (*right*) according to the REPRO-method. The dots indicate the median; error bars indicate the span of tested sites [109]

amount of carbon in the residues that can be regarded as effective for humus formation. The scientific discourse on the definition of scientifically secured values is not terminated yet [110, 113–115].

Biodiversity

The increased cropping of energy crops is falling into a time in which a preceding reduction of biodiversity in Europe has been observed (e.g., [116]). Model-based

evaluations, which attribute negative impacts for energy plant production (e.g., [117, 118]), often have the weakness that they do not allow for a differentiated analysis of cropping techniques. Other approaches focusing on this aspect could – in the analysis of different cropping systems – point out that the different energy plants that can be used can provide habitat for a variety of wild-living species.

To answer the question on what impact can be expected from an extended energy plant production,

not only the chosen energy plant species has to be regarded. More importantly, each plant in its spatial context has to be analyzed. This means that besides the habitat conditions during the course of management and the development of the crop stand itself, the neighboring structures have to be taken into account.

The most important finding is that, in a cultural landscape, each crop can contribute to biodiversity, depending on the grade of differentiation from the other crops under cultivation regarding its characteristics such as cropping time span, horizontal and vertical vegetation structure or flowering. The more diverse a regional cropping structure, the higher the probability that wild-living species can find suitable habitat conditions. This effect is demonstrated for plant species and fauna (ground beetles, spiders, and apidae/syphidae) (Fig. 28) [78].

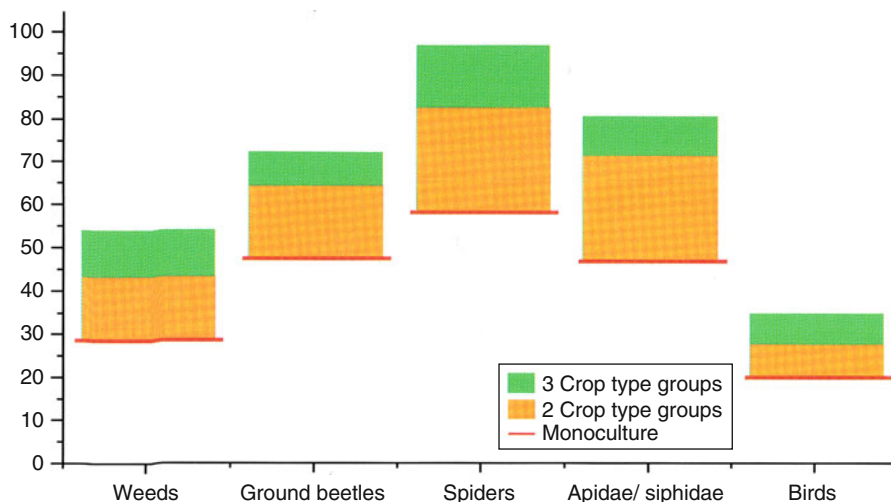
The Figure shows the number of species occurring, depending on the number of crops in the crop rotation. The number of individuals of the different species or the level of coverage of weed species/side flora is not increasing parallel to the number of species. It can rather be quantified by the mean of the individuals that can be observed in the single crops. If the number of crops in a rotation is reduced down to monocultures, the species number is reduced, too. The danger of

the prevalence of single organism types is increasing significantly [78].

Positive impacts on the species number of most organism groups can be expected by an increased cropping of perennial crops. As an example, the cropping of perennial forage crops provides habitats for species that can only seldom be found in other crops. Examples of such species include species whose occurrence is dependent on a period of resting soil for several years such as grasses in general, rhizomatic species and hemikryptophytes and when regarding fauna, species that are active throughout the whole year, such as some spiders and some apidae/syphidae are notable examples. Perennial forage crops also provide hibernation possibilities which other crops lack [119].

Multi-cut perennial forage crops might also become a trap for some species, since high cutting frequencies and especially the first cuts in spring times might lead to a destruction of the clutches of ground-nesting birds [120]. The same applies to whole-crop cereals that are harvested earlier than cereals produced for grain use.

On the other hand, the combination of whole-crop cereals harvested comparably early with second crops, as described above (double-cropping system, Fig. 20c), can lead to a prolonged habitat utilization period for



Biogas Production and Energy Crops. Figure 28

Species number of different organism groups in crop rotations containing high shares of energy plants depending on the number of crops included into rotation systems. Base EVA-Project (Data from Thuringia, Bavaria, Mecklenburg-Pommern for 2005–2007.) Values for birds are based on a consultation of experts and are inflated by a factor of 10 [78]

the different organism groups. Another example, for land use change leading to a multitude of effects that are positive and negative for biodiversity, is the fact that early cuts might lead to a decreased spreading of weeds. For example, 35% of flowering plants occurring in winter cereal stands and 25% of flowering plants in spring cereals do not reach seed ripeness in the case of whole plant harvest [78]. From the viewpoint of the farmer, this might be an option for weed regulation and the minimization of herbicide treatments, especially when taking the multiresistance of some weed species into account.

A differentiated view on the impact of different crops can be observed in the occurrence of flower-visiting animals. While winter wheat provides good conditions for the occurrence of solitary bees, bumblebees and hover flies are rather to be found in maize. Depending on the importance set on the occurrence of organisms, the evaluation of different energy crops is therefore variable. In the end, the evaluation of the impacts of feedstock production for anaerobic digestion on biodiversity amounts to the question, if the energy plant production with its various options results in an extended variety in cropping structures or if in a mid-term perspective, no such extension will be the case. For an evaluation of the different options, regional cropping structures should be taken into account. The fact that an extended cropping of silage maize is not necessarily leading to a reduction, can be shown at the cropping structure of the “Saale-Holzland-Kreis” as part of the “Quality wheat region” mentioned above. The cropping for silage maize in 2007 was less than a quarter of the area for winter cereals. An extension of the maize cropping area would therefore be linked to an increased biodiversity in organisms, whose population development takes place in late summer, for example, summer-flowering plants, as part of the flora, or ground beetles larvally hibernating as well as summer-active spiders and syrphidae.

Future Directions

The utilization of energy plants for biogas production provides chances for a sustainable provision of quantities of substrate which are not available from other sources. Solar radiation that is saved in the substance

groups of biomass can, in the following utilization chain, be stored and, after anaerobic fermentation processes, be used in the form of methane. The utilization chain allows for a steady-going electrification or the upgrading of biogas for the feeding in of methane into the gas grid.

The particularity of biomass production for energy purposes is the fact that it is always part of the existing agrarian (eco-)systems and can therefore complement these. Chances therefore exist that biomass production can be seen as a structuring element, which can provide chances for farming income diversification, extension of crop rotations, risk diversification, and the equaling out of work peaks as well as for sustainability targets such as biodiversity and climate gas mitigation.

As for future directions, it becomes obvious that the extension of biomass production is not leading to the achievement of the variety of the different goals per se. In fact, the application of sustainable farming options for biomass production and the achievement of societal goals are also linked to the question, to what extent the application of these systems is interesting from the economic point of view of farming practice. Since in most cases energy farming is dependent on public subsidies, the challenging task is resulting to design mechanisms that in the context of volatile markets for agricultural goods can keep planning security and the long-term character of targets in focus and avoid bringing forward systems that are based on the pursuance of one-sided and short-term goals.

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Biogas Production, Developing Countries

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Glossary

- ABR** Anaerobic baffled reactor
- ADB** Asian Development Bank
- AF** Anaerobic filter
- BOD** Biological oxygen demand
- BORDA** Bremen Overseas Research and Development Association
- CAMARTEC** Centre for Agricultural Mechanization and Rural Technology
- COD** Chemical oxygen demand
- CSSES** Centre for Sustainable Environmental Sanitation
- DEWATS** Decentralized wastewater treatment systems
- DM** Dry matter
- EGSB** Expanded granular sludge bed
- FB** Fluidized bed
- GATE** German Appropriate Technology Exchange Centre
- GIZ** Gesellschaft für Internationale Zusammenarbeit - German International Cooperation
- HIV** Human immunodeficiency virus
- HRT** Hydraulic retention time
- IADB** Inter-American Development Bank
- IC** Integrated circulation
- IFAD** International Fund for Agricultural Development
- KfW** Kreditanstalt fuer Wiederaufbau - German Development Bank
- NGO** Nongovernmental organization
- ODM** Organic dry matter
- PVC** Polyvinylchloride
- R&D** Research and development
- SEI** Stockholm Environmental Institute
- SIDO** Small Industries Development Organisation
- SNV** Netherlands Development Organisation
- SRT** Solid or sludge retention time
- TED** Technologies for Economic Development
- UASB** Up-flow anaerobic sludge blanket
- USTB** University of Science & Technology Beijing
- WASAZA** Water and Sanitation Association of Zambia

Definition of the Subject

Energy is essential for human development. Without an adequate basic energy supply, people cannot cook their food, light their homes, or keep food and drinks chilled for storage. Alongside the introduction of efficient and clean thermal use of waste biomass for

cooking, the provision of electricity from renewable energy sources can provide basic energy services for lighting and communication and promote local economic growth.

Biogas-producing (anaerobic) treatment units as part of an integrated waste-to-energy treatment system are an alternative to use waste biomass as feedstock due to their energy and soil conditioner production capacity, low-tech components, and adaptability. It is also an excellent technology for treatment and reuse of manure and straw, organic sludge treatment collected from septic tanks, holding tanks, dry toilets, or for organically loaded wastewater pretreatment.

Decentralized low-tech biogas system solution provides a unique possibility for promoting appropriate household and community scale solutions to social and environmental problems; it is apparent that worldwide still many people are seeking friendly, small scale solutions for themselves and their communities, including biogas systems with lower specific performance efficiency, but out-balanced with lower degree of system mechanization and larger construction volumes.

Several research institutions and international agencies rate biomass as one of the cheapest available renewable energy sources for heat and power generation. Furthermore, conversion from biomass to useable energy is a low-carbon process as the resulting CO₂ is captured by plant regrowth. In contrast to other renewable energies, biomass energy conversion technology can generate heat and power on demand at flexible time, as long as a sufficient supply of feedstock is assured. Many municipal, agricultural, and livestock residues can provide feedstock for bioenergy conversion without increasing land requirements.

The main advantages of the anaerobic treatment process compared to the aerobic treatment process are the generation of biogas and significantly less sludge production. The fact that the plant nutrients phosphorus and potassium are not removed in the treatment process can also be an advantage for the application of the effluent in agriculture to replace chemical fertilizer, but the final effluent should never be discharged directly into water bodies without further treatment, unless the carrying capacity of the receiving water body is not exceeded.

Often industrialized countries neither have sufficient experience nor appropriate technologies to build on in developing countries. Transferable experience in low-tech biogas systems was identified in 1978 first in India and China and transmitted initially by a South-North-South transfer during 1980–1993 by international development cooperations. In the first decade, biogas technology focused on small-scale farmers. At a later stage, also larger farms as well as waste treatment issues increasingly became the additional focus of biogas technology. The term “appropriate technology” seemed justified by the fact that low-tech biogas systems are still adapted to the respective local conditions during a “learning-with-developing-countries” process.

Introduction and Development History

The topic “biogas” is relevant to all areas of rural development. Often overlooked, biomass is the most important renewable energy source in developing countries. Nearly one third of the world population cooks on open fires or traditional stoves with biomass (like wood, dung, straw, and agricultural waste). When cooking on biomass in huts, without chimney, flue gas causes significant respiratory and eye disorders. Therefore, the use of chimney-connected wood-saving stoves and biogas as clean cooking fuel is indispensable for improving health of women and children.

Inadequate sanitation in developing countries is a big issue. Moreover, manure, slaughterhouse waste, and untreated sewage pose major problems to health and environment. To use the energy potential of wastewater and waste, these organic substances can be treated in anaerobic (biogas) plants. The biogas produced can be used for cooking, lighting, heating, and cooling, and – if sufficient – to run engines. As a by-product, a valuable organic fertilizer is produced. Biogas plants therefore provide not only advantages for environment and sanitation, often, the most important aspect is the localized energy production and supply with biogas.

Due to the increasing awareness on climate change impacts, eco-friendly renewable energies are nowadays more in demand than ever. In relation to

these changing conditions and technical developments, biogas as a greenhouse gas neutral source of energy is an often-discussed topic in developing countries.

There are different expressions used for the same technology: anaerobic digestion, biogas plants, anaerobic fermentation, and biogas-sanitation system. The technology has been used for excreta treatment now for more than 100 years; thus, biogas is for sure the oldest “modern” renewable energy. Anecdotal evidence indicates that combustible natural gas (obviously natural gas, or marsh gas from swamps) was used for heating bath water in Assyria during the tenth century BC and in Persia during the sixteenth century BC. The science of anaerobic digestion is as old as scientific research can be and includes the names of world’s most famous researchers.

The word methane comes from the Greek “Μεθάνιον αέριον” (*Methanion Aerion-swamp or foul air/gas*) and thus shows that the Greeks already centuries ago knew about the flammable gas. In Asia Minor, in places where ignited natural gas (methane) sources have been well known, is a volcanic area in which such gases occurred and this gas was named *Methana*. The alchemists in the Middle Ages knew methane as a swamp gas under the name *marsh gas*.

One of the earliest scientific “methane” gas discoverers was the Belgian Jan Baptista van Helmont (1579–1644) in 1630; his knowledge is documented in a communication about an inflammable gas “*gas pingue*” emanating from decaying organic matter. In 1667, the British Thomas Shirley (1638–1678) described “coal bed methane gas” more precisely in a brief report entitled “*A Well and Earth in Lancashire taking Fire at a Candle*” in the “Transactions of the Royal Society,” about his observations in February 1659. The Italian Alessandro Giuseppe Antonio Anastasio Volta (1745–1827) wrote a letter on November 14, 1776, about a combustible gas “*Aria inflammabile nativa delle Paludi*” evolved when the bottom sediments of ponds near the town of Como, northern Italy, and in the Lake Maggiore, were stirred. He experienced that the gas exploded when mixed with air and ignited; he even determined the gas-to-air ratio that resulted in the loudest explosion. It was in 1804 when the British

John Dalton (1766–1844) established the chemical constitution of methane. The gas attracted the attention of famous scientists of those days. The British William Henry (1775–1836) deduced the probable identity of the synthetic illuminating gas as methane. In 1806, he showed that Volta’s gas was identical with methane gas.

The first allusion to animal manure came from the British Sir Humphrey Davy (1778–1829), who reported the presence of combustible biogas in fermenting farmyard manure, in 1808. Therefore, he can be considered as the first real discoverer of biogas as a mixture of methane and carbon dioxide.

By that time the physical scientists (physicists and chemists) had advanced knowledge about biogas as far as their knowledge allowed, and from thereon the microbiologists took over the scientific investigation on biogas. In 1868, the French microbiologist Mme. Antoine Bechamp (1816–1908) identified the micro-organism responsible for methane production. She showed as well that different fermentation products are formed during the digestion process, depending on the type of substrate. The Russian Leo Popoff from Petersburg published 1875 in Strasbourg, Elsass, that fermentation of cellulose could form *swamp gas* at temperatures still as low as 6°C. His experimental studies brought out the optimum temperature for their action and the effect of antiseptics, with some knowledge of the gaseous decomposition products.

The first attempts in using biogas in France were undertaken when the French Ulysses Gayon (1845–1929) produced biogas energy from animal manure. In 1875, he became director of an agricultural research institute in Bordeaux. His trials to produce biogas from manure and to use this gas for lighting and heating were published in the *Comptes Rendus of the Séances de l’Académie des Sciences*, tome 90, 1884. Dr. P. Duvernay reported about this event on March 5, 1884, in the daily newspaper “Le Figaro” under the title “*Une Drôle d’Eclairage*.”

Already earlier, in 1881, the French journal *Cosmos* cited the first full-scale anaerobic treatment of domestic wastewater as “*Mouras Automatic Scavenger*.” Louis Mouras of Vesoul, France, obtained

a septic tank patent in 1881 and was credited with this invention. Baffles, which regulate the flow and increase sanitization, were added in 1905 in order to make the septic tank more efficient. It is reported that this kind of septic tank without biogas recovery was introduced in the USA in 1883, in England in 1895, and in South Africa in 1898. Anaerobic digestion is therefore the oldest technology applied for domestic wastewater treatment. Since 1850 until this date, open constructed rectangular settling tanks (cesspools) were operated intermittently, meaning that the sewage inflow had to be stopped regularly for sludge removal.

In 1895, Donald Cameron, City Surveyor of Exeter, England, constructed in this town a line of six “*Mouras*” septic tank, covered to avoid smell, as the tanks were placed near dwellings. From 1911 onward, under the guidance of Mr. T. Moulding, the collected biogas was used in sewer gas destructor lamps, a type of street gas lighting.

Combustible biogas that could be obtained from human excreta was also demonstrated in India, where in 1897 a biogas-generating plant treating toilet wastewater was constructed in Matunga, more specifically in the Homeless Lepers’ Asylum, known as the Acworth Leprosy Hospital in Wadals, founded 1890. The biogas was used for lighting. This may be the first application worldwide of the so-called biogas-sanitation.

The roots of technical applicability of microbiological digestion probably lie with methane-producing bacteria “*Methanobacillus omelianskii*” discovered by the Ukrainian Vasilii L. Omelianskii (1867–1928). From 1893 to 1928, he worked in the department of general microbiology of the Institute of Experimental Medicine. His classic studies on methane fermentation bacteria were reported during 1903/1904. He isolated organisms that produced hydrogen, and acetic and butyric acids. He also reported the formation of methane from hydrogen and carbon dioxide. The development of microbiology as a science led to more research by the American team A.M. Bushwell, G.E. Symons, C.S. Borrruf, and W.C. Boyle; they published in 1936 a scientific formula describing the composition of biogas based on the chemical composition of the substrates undergoing an anaerobic digestion process.

William Owen Travis sought to improve the contact bed procedure for municipal wastewater treatment. As local health officer in charge of a contact filter at Hampton, England, Dr. Travis was quite familiar with the problem of bed clogging. His solution, introduced in 1904 as the *Travis Hydrolytic Tank*, was essentially configured as a multistage septic tank. Successively divided into detritus, hydrolytic, and finishing tanks, the latter two zones contained wooden baffles or laths placed in a parallel array. These baffles were intended to retain fine particles for subsequent degradation. Based on this development, Karl Imhoff (1876–1965) shifted the focus from anaerobic wastewater treatment to anaerobic sludge treatment with his *Imhoff tank* (1905/1906). An upper section of this tank is designed for sedimentation; the solids fall from it through a slot into a lower section for digestion. Experiments on a similar unit, called Biolytic tank, were carried out in the USA between 1909 and 1912. With the installation of the first sludge heating system, separate digestion of sludge was reported at the Essen-Rellinghausen wastewater treatment plant in Germany in 1927. The separated sludge digestion became increasingly popular in larger German towns and cities, and the importance of methane gas generation was widely recognized. Methane gas was used for digester heating; it was collected and delivered to municipal gas systems, and it was used for power generation for operating biological wastewater treatment systems, and as transport fuel. The sale of sewage gas was, in addition to the sale of sewage sludge as fertilizer, one of the few ways from which the sewage treatment plant could generate revenue to reduce wastewater treatment costs. In the USA at Belleville Water Works, Maryland, Illinois, the first *Clarigester* was installed in 1938 to separate the sludge from the wastewater stream, and to treat the sludge anaerobically, recovering sewage biogas.

In China in 1927, Luo Guorui developed in Shantou city, Guangdong province a small-scale agricultural biogas plant, using the gas for lighting; the design was based on existing urban household septic tanks. This may be considered as the worldwide first agricultural biogas digester.

Inspired by the research work of the Rothamsted agricultural experimental station in England in

1929, the British Lord Iveagh was the first builder of a European agricultural biogas reactor on his property in Pyrford Court, Surrey. He had a 300 m³ volume biogas tank and used straw as feedstock, which was inoculated twice a year with fresh manure. For 20 years, the daily gas production was recorded, which indicated daily 12–120 m³. The gas was used on the farm even for cooking and lighting. It was used until 1960, before it ceased operations.

G. Ducellier and M. Isman developed the design and prototypes of another dry-fermentation biogas digester since 1937 at the Institute of Agriculture in Algeria. Since 1946, the technology had been transmitted to France and Mr. Renandat was one of the first farmers at Levroux, Indre, who constructed a biogas plant which consisted of a battery of four tanks (100 m³ volume), gasholder and compressor, pressure storage tank, and a biogas-fueled tractor. It was estimated that such an installation would pay for itself within ten years of construction by the production of gas and savings in fertilizer costs. Since then, French farmers constructed perhaps 1,000 low-tech plants along the lines of the *Ducellier-Isman* design.

In India, in 1946, a social worker within the Khadi and Village Industry Commission (KVIC), Mr Jashbhai Patel, started to work on developing a liquid manure biogas digester design placing the digestion chamber below ground.

Imhoff drafted in 1944 an agricultural biogas plant for the farm Zitzstaudenhof in Olching, Germany. Although this plant was never built, the draft, published several times by the designer, gave the model for the first agricultural biogas plant called “*Darmstaedter Gaerkanal - gas factory on a farm*” in 1947/1949 on the farm Bertaloth in Rohrbach; improvements were guided by Prof. F. Reinhold, State Laboratory of Road and Urban Engineering at the Technical University Darmstadt, and built by the Casting and Valve Works Kaiserslautern, Germany.

Nowadays, such low-tech anaerobic reactors are widely adopted for the stabilization of municipal sludge, human excreta, and animal manure, aiming at the generation of renewable energy in the form of methane and the generation of bioslurry.

The National Institute for Water Research of the South African Council for Scientific and Industrial Research published in 1950 research results from G.J. Stander, which recognized the importance of solid retention time (SRT) for a successful anaerobic treatment of different wastewaters. This has been the basis for the worldwide development of the so-called high-rate anaerobic biogas reactors, in which SRT and hydraulic retention time (HRT) are uncoupled, but both fractions are undergoing anaerobic treatments in one constructed tank. Further development led to a wider application of anaerobic biotechnology, particularly for industrial wastewater treatment combined with biogas recovery. Some of the present widely used high-rate anaerobic treatment processes for industrial wastewater treatment are anaerobic filter (AF), up-flow anaerobic sludge blanket (UASB) reactor, expanded granular sludge bed (EGSB), fluidized bed, internal circulation (IC) reactor, and hybrid systems.

Basics of the Biogas Process

Anaerobic digestion is a complex biological process that takes place in the absence of oxygen. The decomposition process is possible under anoxic (presence of nitrate) and anaerobic conditions: Bacteria split organic substances into their components, and these components are “re-arranged”; other bacteria originate from biochemical degradation.

The digestion is a multistage process consisting of hydrolysis, acido- and acetogenesis, and methanation performed by different bacteria and microorganisms. In low-tech biogas systems, the different degrading reactions take place in one or two digester(s) or digestion chambers. The digestion process starts with hydrolysis of the input material caused by exoenzymes of facultative and obligatorily anaerobic bacteria in order to break down insoluble organic polymers such as cellulose, proteins, and fats. Acidogenic bacteria then convert sugars and amino acids into carbon dioxide, hydrogen, ammonia, and organic acids, followed by acetogenic bacteria converting the resulting organic acids into acetic acid, along with additional ammonia, hydrogen, and carbon dioxide. At the end of the process, methanogens convert these products into methane and carbon dioxide.

To summarize, the anaerobic digestion process consists of the following steps:

1. Hydrolysis: (a) The organic matter is hydrolyzed by extracellular enzymes. (b) Bacteria decompose the long chains of complex to simpler substances, for example, polysaccharides to monosaccharides.
2. Acidification: (a) Acid-producing bacteria convert intermediate fermentation products into acetic acid, H_2 , and CO_2 . (b) Acid-producing bacteria create anaerobic conditions for CH_4 (methane)-producing bacteria.
3. Methanization: Methanogens, that is, methane-producing bacteria, acetic acid, and/or hydrogen are used to form methane. Sulfate reduction leads to the formation of hydrogen sulfide.

Higher concentrations of, for example, ammonia, heavy metals, light metal cations, oxygen, short chain organic acids, other organic acids, and sulfides could inhibit the anaerobic process. Short-term biogas productivity tests are available to investigate this.

One result of such an anaerobic digestion is biogas. The term “biogas” refers to a gas produced by anaerobic digestion or fermentation of organic matter including manure, sewage sludge, municipal solid waste, biodegradable waste, or any other biodegradable feedstock under anaerobic conditions. Biogas is comprised primarily of methane and carbon dioxide. In conventional septic tanks, biogas from Imhoff tanks (combined settler and sludge treatment units) and anaerobic lagoons vented out, creating climate critical emissions due to its methane content. The rate of methane production depends on the rate of removed COD, BOD, and the temperature. It is also common to relate the biogas production to the dry matter (DM) or organic dry matter (ODM) of the input material.

Practically most anaerobic bioprocesses stabilize organic wastes that are formed from mixtures of fats, proteins, and simple carbohydrates, and this typically results in biogas composition illustrated below:

- Methane (CH_4): 50–70 vol%
- Carbon dioxide (CO_2): 28–48 vol%
- Other gases: up to 2 vol% including trace components such as hydrogen, nitrogen, oxygen, ammonia, argon, carbon monoxide, hydrogen sulfide, non-methane volatile organic carbons, halocarbons

Biogas-producing systems are used as environmentally friendly technology for waste and wastewater treatment, and for renewable energy generation in many countries. The average calorific value of biogas is about 6 kWh/m^3 ; this corresponds to about half a liter of diesel oil. The net calorific value depends on the efficiency of the burners or appliances. Methane is the valuable component under the aspect of using biogas as a fuel.

Biogas can be used for (in order of simplicity, with simplest option first): cooking with gas stoves, lighting, heating, electricity generation, simultaneous generation of both electricity and useful heat (with combined heat and power (CHP) units), cooling, or as transport fuel. Some options are only feasible for larger biogas systems, but the smallest combustion engine-based “mini” biogas GENSETs – commercially offered – is 4 kVA.

As common figures for methane production $0.25 \text{ m}^3 CH_4/\text{kg COD}$ (chemical oxygen demand) removed or 1 kg BOD (biological oxygen demand) removed results in practice in about 0.6 kg methane at 273 K (energy content of methane 35.8 MJ/m^3).

Sulfur content in biogas in form of hydrogen sulfide (H_2S) has to be taken into account and possibly filtered out or eliminated chemically. H_2S is a colorless gas presenting a strong odor of rotten eggs; it fatigues the sense of smell, which cannot be counted on to warn of the continued presence of the gas. While biogas is used for cooking, the presence of H_2S in the biogas results in smell disturbance and faster corrosion of the cast iron burner parts, which are in direct contact with biogas.

Additionally, a part of H_2S might be converted through the incomplete combustion of biogas into sulfur dioxide (SO_2), which could result in headache and breathing problems. Even it is known that H_2S needs a lower (260°C) combustion temperature than methane (CH_4) at 560°C , temperatures over 850°C throughout the flame are necessary to prevent the formation of carbon monoxide (CO), partially oxidized hydrocarbons, dioxins and furans, and polycyclic aromatic hydrocarbons (PAHs).

Stoichiometrically, 9.6 volumes of air per volume of methane are required to achieve complete oxidation by burning. For the typical biogas composition given above, this ratio reduces to 5.7:1. Similarly, the energy released by pure methane is 36 MJ/m^3 (gross calorific value) and is reduced to 21 MJ/m^3 for biogas.

Organic material degrades more rapidly at higher temperatures because all biological processes operate faster at higher temperatures up to the limit of sterilization. The three ranges of temperatures in which methanogens could work are called psychrophile (8–25°C, with an optimum at 17°C), mesophile (30–42°C, with an optimum at 40°C), and thermophile (53–65°C, with an optimum at 55°C).

Low-tech, non-heated, and poorly insulated biogas systems are often applied in countries where the ambient average annual temperature ranges above 12–25°C. In ambient temperatures below 8°C, digestion capability is very much reduced without active and passive heating and insulation of the digester. The methane formation process is also sensitive to daily temperature variations of more than 3°C; therefore, day-night variations or temperature shock loads have to be kept in a limited range to ensure a steady biogas production. The higher the process temperature the more sensitive is the process (bacteria).

To improve low-tech biogas systems, the application of improved insulation (above and below ground), keeping the plant environment dry (drainage layer and plant area roofing), active and/or passive heating of plant, and filling substrate should be considered (preheating, solar heating), depending on available design, funds, and micro-environment.

Biogas Systems and Their Importance

Biogas systems are defined here as “engineered systems designed and constructed to utilize biological processes which break down solids and soluble organics in the liquid by anaerobic bacteria action under exclusion of free oxygen in treating organically loaded sludge.”

A process design differentiation between highly diluted (low dry matter content) wastewater and solids or sludge (high dry matter content) treatment has to be made. For the first one, bacteria have to be accumulated and kept in the system, while in the second one, organic biodegradable solids are hydrolyzed and then converted into biogas. Anaerobic wastewater treatment, biogas sanitation, bio-waste fermentation, and manure treatment are using the same biological process, but the goal of anaerobic wastewater treatment is to purify wastewater. The goal of animal manure treatment in biogas plants is to generate energy, avoid

methane emissions, and to produce an improved soil conditioner. The goal of biogas sanitation is to prepare “humanure” for safe reuse and to produce biogas. The goal of bio-waste fermentation is to reduce volume of waste for post-treatment and to produce carbon emission free energy, rather than to prepare manure for fertilizing reuse and to produce biogas.

Biogas systems may treat a wide range of waste and wastewater; here a focus is put on biogas production in developing countries (low-tech applications) for small-scale heat and cooking gas provision, by treating animal manure, organic waste from industries and settlements, black water or brown water, excreta, fecal sludge, wastewater from low or no flush toilets, and kitchen waste.

Anaerobic treatment units are often an alternative or a pre-treatment to aerobic treatment systems due to their energy and soil conditioner production capacity, low-tech components, and adaptability. It is also a technology for organic sludge treatment. The main advantages of the anaerobic treatment process compared to the aerobic treatment process are the generation of biogas and significantly less excess sludge production as well as smaller reactors. The fact that the plant nutrients phosphorus and potassium are not removed in the treatment process can also be an advantage for the application of the effluent in agriculture to replace mineral fertilizer. However, the effluent should never be discharged directly into water bodies without further treatment, unless the carrying capacity of the receiving water body is not exceeded. Anaerobic technology has advantages in terms of nutrient recycling, energy balance, and CO₂ emission reduction compared to conventional aerobic treatment systems.

Toilet wastewater alone could not produce enough biogas to cover completely the energy demand for cooking or lighting of a household, at least the excreta of five persons are needed to cover the daily cooking energy demand of one person. Feeding easy biodegradable organic kitchen waste or animal dung into the biogas-sanitation digester could increase the biogas yield. An organic garbage disposal unit in the kitchen sink (grinder) is useful in this respect.

In decentralized or semi-centralized wastewater treatment systems, biogas-sanitation units are often designed as primary treatment of wastewater to remove large particles and some organic matter by settling and digestion.

Besides the feedstock material, local circumstances must be taken into consideration before designing a biogas plant, such as the dilution of the influent with (gray) water or urine; addition of organic waste; the settle-able solids content in the influent; the climate and soil temperatures; available space; and the intended reuse or disposal pathway.

Methane (CH_4) is a greenhouse gas that remains in the atmosphere for approximately 9–15 years. Methane is 21 times more effective in trapping heat in the atmosphere than carbon dioxide (CO_2) over a 100-year period. It is emitted from a variety of natural and human-influenced sources. Human-influenced sources include landfills, natural gas and petroleum systems, and agricultural activities; coal mining; stationary and mobile combustion; wastewater treatment; and some industrial processes. Methane is also a primary constituent of natural gas and an important energy source. As a result, efforts to prevent methane emissions or utilize methane can provide significant energetic, economic, and environmental benefits.

Biogas systems can be classified according to various parameters; the three most important design criteria are (1) hydraulic retention time (HRT in days), (2) organic load rate (OLR in kg COD/m^3 or kg ODM/m^3 active fermenter volume), and (3) settled sludge retention time (SRT in days or years).

The required hydraulic retention time (HRT) of the substrate in the digester depends on the process temperature and the type and concentration of the substrate itself. This will then determine the volume of the digester. Digesters are generally designed for an optimum economic balance between highest biogas yield and smallest volume (HRT). Therefore, the retention time is chosen as the total time required, producing a certain amount of the total biogas (to size the digester to obtain all possibly generated biogas is often not economically viable). A low-tech energy-optimized biogas system should have a minimum of 20 days of hydraulic retention time due to bacterial reproduction time, but from a health point of view, the hydraulic retention time in a biogas-sanitation system should be extended to more than 60 days, if no adequate post-treatment of effluent is foreseen.

For animal manure undergoing low-tech fermentation process in the upper psychrophilic and lower mesophilic temperature range ($17\text{--}33^\circ\text{C}$), the

following approximate hydraulic retention time values are usually applied:

- Cow or cattle manure: at least 30 days
- Pig manure: at least 25 days
- Poultry manure: at least 40 days
- Animal manure mixed with easy biodegradable plant material: about 80 days
- Fecal material: at least 60 days

A sludge retention time (SRT) of at least 10 days is necessary to promote methanogenesis in the anaerobic treatment of primary sludge at a process temperature of 25°C while a sludge retention time of 15 days is necessary for sufficient hydrolysis and acidification of lipids. For temperatures as low as 15°C , a sludge retention time of at least 75 days has to be considered to achieve methanogenic conditions. The longer the sludge retention time, the better the degradation and stabilization of the sludge will be and less sludge will remain. This is of special importance for biogas-sanitation units; the handling of not-sufficient treated sludge can be also a problem in densely populated areas.

Parameters for monitoring anaerobic processes are: organic dry matter content, pH value, carbon-to-nitrogen ratio (C/N ratio), redox potential, volatile fatty acids, moisture content of the biogas, temperature stability, and substrate composition. Biogas amount and quality should be used for monitoring the plant performance – related to the applied feedstock biogas potential; the total solids content in the reactor influent and effluent is an important parameter, too.

It is always important to maintain by weight a carbon-to-nitrogen (C/N) ratio between 8 and 30:1 for achieving an optimum rate of digestion. Combining materials low in carbon with those that are high in nitrogen can manipulate the C/N ratio. If the C/N ratio is very high, nitrogen limitation could cause low gas production, since nutrients for the growth of anaerobic bacteria are lacking. If the C/N ratio is very low, the pH value may increase, and will have a toxic effect on bacteria, and also result in lower biogas production.

Different types of biogas digesters could be combined (so-called combined systems, multistep systems, or decentralized wastewater treatment systems) in order to benefit from the specific advantages of the different systems. The quality of the final effluent

from the systems improves with the multiple steps of the treatment facility. Design and engineering information for the worldwide used fixed dome, baffle reactors, anaerobic filter, covered lagoon, stirred systems, up-flow systems, or composite plant design variations are available through many websites, literature, and expert consultations.

Local design adaptations to different local human diets, livestock keeping habits and manure types (influencing organic load and biogas potential), sanitization needs, and effluent reuse options (for energy crops, tree nursery, grassland, vegetable, grains) are always necessary.

Selected Low-Tech Biogas Design and Post-Treatment Units Descriptions

Below some selected low-tech biogas designs are described. The key to the optimal operation of a reactor selection and design is to understand the bacteria: how much, how active, how good in resisting shock loads.

Fixed Dome Digesters. Chinese model biogas plant with manhole (also called drum-less digester) consists of an underground compartment (fermentation chamber) with a dome on the top for gas storage. In this design, the fermentation chamber and gasholder are combined as one unit. The construction details of a biogas plant (with or without baffle(s), size of integrated gasholder) depend on the further treatment step chosen and on the expected biogas use pattern. In a special design, the so-called biogas settler (BS), to achieve that the sludge retention time (SRT) is longer than the hydraulic retention time (HRT), baffle or separation walls should be added when it is operated as stand-alone sanitation system. The accumulated settled sludge must be removed from the base of the biogas settler (BS) periodically.

Floating Drum Digesters. In the digester chamber, a floating drum (bell) is placed on top of the digester to collect the biogas produced from the digester. Thus, there are two separate structures for gas production and collection. The construction details of a biogas plant (with or without baffle) depend on the further treatment step.

Covered Lagoon Digester. A sealed pond or lagoon operated for the stabilization of manures, anaerobically and fitted with an impermeable cover (polyvinyl

chloride (PVC), ethylene propylene diene monomer rubber (EPDM), or high density polyethylene (HDPE)) to capture the biogas generated as the product of waste stabilization. Disadvantages are the land area needed for anaerobic lagoons and sludge sedimentation problems, if digester is un-stirred.

Plug-Flow Biogas Digester. Plug flow is a simple model of the velocity profile of a fluid flowing in a pipe. In plug flow, the velocity of the fluid is assumed to be constant across any cross section of the channel perpendicular to the axis of the channel. Essentially no back mixing is assumed with “plugs” of fluid passing through the reactor. Many different forms of construction are known, for example, fixed-dome tunnel plants, floating gas holder tunnel plant, PVC or PE-plastic bag “sausage” tubular digester, composite tank plant, covered sedimentation channel lagoons. The digester is a long, rectangular container or tank or channel (1/5: about 1 times large related to 5 times long), with gastight cover. New material added to the tank at one end pushes older material to the opposite end.

Anaerobic Baffled Reactor. The anaerobic baffled reactor (ABR) has a series of up-flow and down-flow baffles which are used to direct the flow of wastewater in an up-flow mode through a series of sludge blanket reactors. This configuration provides a more intimate contact between anaerobic biomass and liquid, thus improving the treatment’s performance. It could be used as primary treatment as well, especially where influents are highly diluted with flush water (from pig stable or toilet buildings). Separation of the sludge retention time (SRT) from the hydraulic retention time (HRT) is the key to the successful operation of an anaerobic baffled reactor. Due to this fact, a baffled reactor is considered as the best alternative to aerobic treatment and posterior to primary settlement in a biogas digester. The treatment efficiency achievable is usually superior to that of a conventional septic tank.

Anaerobic Filter. The anaerobic filter (AF) is suitable for effluents with a low content of suspended solids and a narrow COD/BOD ratio, for instance, from biogas settlers or biogas septic tanks or anaerobic baffled reactor as initial treatment unit. The bacteria in the filter are immobile and generally fix themselves to solid particles (carrier material) or to the reactor walls. Filter materials like rocks, cinder, plastic, or gravel provide additional surface area for bacteria to settle. The larger

surface area for the bacterial growth helps in the quick digestion of the wastes. A good filter material provides a surface area of 90–300 m²/m³ reactor volume. Anaerobic filters are reactors consisting of supporting material layer. On the surface of these material layers or bed fixation of microorganism the development of biofilm takes place. In the case of concentrated feedstock, the risk of blockage of the filter material increases with the concentration of suspended solids. Therefore, it is best suited for posttreatment.

Up-flow Anaerobic Sludge Blanket Reactor. The up-flow anaerobic sludge blanket reactor (UASB) is a tank filled with anaerobic granular or flocculants sludge with good settling properties. (The bacteria spontaneously agglomerate to form granules.) Influent wastewater is distributed at the bottom of the UASB reactor and travels in an up-flow mode through the sludge blanket. The anaerobic degradation of organic substrates occurs in this sludge blanket, where biogas is produced and serves to mix the contents of the reactor as they rise to the surface. The UASB reactor has the potential to produce higher quality effluent than biogas septic tanks, and can do so in a smaller reactor volume. The design of an UASB reactor must provide an adequate sludge zone since most of the biomass is retained there. The granulated sludge zone is completely mixed because the wastewater is fed into the reactor through a number of regularly spaced inlet ports. The UASB is also characterized by a much longer SRT in comparison with the HRT.

Development of Biogas Use in Various Countries

In the following some developing country programs and developments in the biogas sector are briefly described; the list is however incomplete as about all countries have nowadays their own biogas history.

Asia

Bangladesh The Institute for Fuel Research and Development (IFRD) of Bangladesh Council of Scientific and Industrial Research (BCSIR) has been the main actor for the dissemination of domestic biogas plants in Bangladesh till date. Other organizations being involved at different stages have been Bangladesh Rural Advancement Committee (BRAC), Local Government Engineering Department (LGED),

Department of Environment (DoE), Grameen Shakti (GS), Bangladesh Agricultural University (BAU), Bangladesh Small & Cottage Industries Corporation (BSCIC), Danish International Development Agency (DANIDA), and Department of Livestock Services (DLS).

In 1972, BAU set up a first floating-drum plant in the University campus to study the characteristics of gas production, followed later by a plant that provided gas for cooking and lighting for a family of six members. In the campus of BCSIR, another plant was constructed by IFRD in 1976, followed by a plant at the KBM College in Dinajpur in 1980. Seventy-two plants were constructed for farmers with technical assistance by IFRD. In 1981, DoE started its program through which about 150 floating-drum and 110 fixed-dome plants were installed by contractors free of cost. Other efforts were undertaken by BSCIC (a number of plants), DANIDA and LGED (more than 200 trench and bag type digester), and DLS (about 70 plants). Also the Grameen Bank installed 17 polyethylene plastic bag digesters. Under the “Fuel Saving Project” implemented from 1989 to 1991, IFRD trained local youths who constructed in total 146 plants in the premises of well-to-do farmers. The gasholder was supplied free of cost. In 1994, LGED supported the establishment of an ecological village (Amgram in Madaripur district) among others by converting 95 open latrines into family biogas-sanitation plants.

An important dissemination push was delivered by the “Biogas Pilot Plant (1st phase) Project” implemented by BCSIR in the period July 1995 to June 2000. In total, 4,664 fixed-dome plants were constructed throughout the country. BCSIR employed and trained 128 diploma civil engineers who were assigned responsibilities for motivation, installation, and after-sales service throughout the country. In addition, 898 youths were trained to support the project. The biogas farmers received an investment subsidy of Taka 5,000 (US\$ 64) under the project. Memorandum of Understanding (MoU) were signed between BCSIR and several other institutes like BRAC, LGED, and DLS for research, training, and dissemination of the biogas technology. The cooperation with BRAC was the most successful as this organization managed to motivate about 1,200 farmers. An interim evaluation report in 1999 reported 99% of the plants installed under the

project were in operation, while 91% of the owners could meet their household fuel demand through biogas. Bioslurry from the biogas plants was used in horticulture, pisciculture, and agriculture. The average saving per plant amounted to Taka (US\$ 10) per month.

As the first phase was successfully completed and the potential for biogas in Bangladesh considered huge, BCSIR implemented the second phase of the Biogas Pilot Plant in the period July 2000 to June 2004. The target for this phase was to put on 20,000 biogas plants, out of which 17,194 plants were finally realized. The investment subsidy for the owner was increased to Taka (US\$ 96) per plant. In addition to the diploma civil engineers employed and paid on a monthly basis by BCSIR, an agency system was introduced on incentive basis. About 50 agencies were recognized in defined areas (mostly districts) and received a lump-sum fee of Taka (US\$ 64) per plant as service charge. About 1,000 masons and youths were trained under the project as well.

In the period from October 1998 to June 2003, the LGED implemented a parallel biogas project aiming to install 1,900 domestic plants. As the investment subsidy for this project amounted to Taka (US\$ 64) only, it proved to be rather difficult to motivate farmers during the implementation of the second phase of the Biogas Pilot Plant Project when BCSIR was providing a subsidy of Taka 7,500 to farmers. Therefore, the LGED project was terminated prematurely, after having constructed about 1,120 biogas plants. Under the Secondary Town Infrastructure Development Project-II, another 20 domestic biogas plants were installed using human excreta only.

Of more recent date is the initiative of GS aiming to construct not less than 200,000 biogas plants within a period of five years. This initiative is still in the preparatory phase; at the time of the mission a total of 10 plants were installed or under construction. Agency holders also continued to construct plants without any subsidy in very limited numbers after the termination of the second phase of the BCSIR pilot project in June 2004. By the end of 2008, about 40,000 family-sized low-tech biogas plants of different designs had been installed throughout Bangladesh.

Since 2006, Netherlands Development Organisation (SNV) is implementing the “National Domestic

Biogas and Manure Programme” (NDBMP) in Bangladesh involving the “Infrastructure Development Company” (IDCOL), and other national and local partner organizations. The overall objective of the NDBMP is to further develop and disseminate domestic biogas plants in rural areas with the ultimate goal to establish a sustainable and commercial biogas sector in Bangladesh. This program will help to attain Millennium Development Goals (MDG) set by Government of Bangladesh as well. The overall objective of the National Domestic Biogas and Manure Programme (NDBMP) is to develop and disseminate domestic biogas plants in rural areas with the ultimate goal to establish a sustainable and commercial biogas sector in Bangladesh. The National Strategy for Economic Growth, Poverty Reduction and Social Development prepared by the Ministry of Finance and Planning also puts emphasis on “creating a policy environment that is capable of providing right incentives to adopt new technologies.” It also emphasizes the integration of environmental conservation strategy into national poverty alleviation strategies. NDBMP further contributes to achieve millennium development goals set by the Government. Contribution of biogas in this regard will help poverty reduction through (1) savings on energy expenditure, (2) increased agriculture production by maximum utilization of bioslurry as fertilizer, (3) gender equality through empowering women in decision making and maximization of their participation in the program, (4) improved health through provision of clean cooking energy, (5) improving sanitation by toilet construction connection to the biogas digester, and (6) creation of opportunities for local employment.

Until April 2009, about 35,000 plants were already newly installed in Bangladesh. Considering only smaller sized household biogas plants the total technical potential from the available raw material reaches up to about a potential of three million biogas plants. Under the on-going program a total of 37,269 plants are aimed to be constructed in the period 2006–2012. Several activities are implemented to achieve this target: promotion and subsidy administration to provide Taka 9,000 (US\$ 115) per household as investment subsidy. To ensure proper functioning of the plant, guarantee on plants for 5 years and maintenance services are provided for 3 years, and training on

operation and maintenance will be provided to each biogas plant owner family. Trainings will be developed and imparted to the staff of the partner organizations to strengthen their capabilities. Proper management and utilization of bioslurry is given high emphasis. IDCOL plays a role of refinancing whereas another program implementing organization will be engaged for program activities of the (technical) implementation. This program is subsidized by the Government of Bangladesh, the Netherland development cooperation, local Micro Finance Institutions, and supported with development cooperation loans by the German Bank for Reconstruction and Development (KfW). In addition to these budgetary sources, there is an opportunity of generating carbon finance through trading carbon emission reduction from well-performing biogas plants.

China In 1927, Luo Guorui developed in Shantou city, Guangdong province, a small-scale agricultural biogas plant, based on existing urban household septic tanks. As a standard, the toilet and the pigsty were connected to an underground 8 m³ digester. The *Shantou Guorui Natural Methane Gas Lamp Company* has commercially promoted the system. In the *Shantou* newspaper in 1930, he advertised the benefits of natural methane lamps. The inventor moved in 1931 to Shanghai and founded the *Chinese Guorui General Natural Methane Company* with many branches along the Yangtze River and in the southern provinces. In April 1935, Chinese lecture notes about *Guorui methane digesters* were published as the first scientific presentation about low-tech household-based agricultural biogas technology in the world; this publication initiated the first wave of biogas application in China.

Since 1957 biogas research and technology were developed at high speed, and the Chinese government promoted farm biogas technology vigorously. At the Beijing Agricultural University, 1958, the first “international” training course on low-tech biogas technology was held with Soviet Union invitees. The technology was found to be appropriate to both the livelihood systems of rural farmers and the political intention of the communist party to become independent of fertilizer imports. Up to seven million biogas units have been constructed in China between the years 1968 and 1978. The main feedstock was pig manure,

and the main emphasis of the Chinese program was to provide an efficient and economic fertilizer, rather than household energy aspects of biogas technology. One of the lessons learned from this Chinese biogas program is that technology dissemination to a very large number of households is possible if it is supported by a strong political will.

The today worldwide known Chinese round shaped fixed-dome biogas plant was developed in 1973, and in 1980 – after 7 years of experience and adaptations – it was standardized nationwide. In 1980, the China Biogas Association was founded to coordinate the biogas development inside the country and internationally.

In 1978, the Zhangzhou College of Education developed a small-scale three-chamber biogas-sanitation digester for anaerobic treatment of excreta from household toilets, which was added to the agricultural standards. In 2000, the composite fiberglass household biogas plants entered the commercial market with volumes between 6 and 10 m³. This prefabricated biogas digester offers some significant improvements: improved gas tightness, long life span, lower maintenance costs, and shorter construction period from at least 10 days with brickwork and concrete to half a day. Since then, other prefabricated models, mainly based on high-density polyethylene (HDPE) material, have been developed and entered the market as well.

In 2003, the national biogas development plan for China 2003 till 2010 suggested to increase the use of biogas until the year 2005 from 11 million households to 20 million households, promoting biogas use in one of ten agricultural households. In 2010, the number of biogas-using households reached 40 million, with an operational rate of at least 60%, as estimated by Chinese evaluations. Since 2003, the government subsidizes each low-tech biogas plant with an average of 1,000 CNY (about 110 €).

India In 1946, a social worker within the Khadi and Village Industry Commission (KVIC), Mr Jashbhai Patel, started to work on developing a biogas design placing the digestion chamber below ground. Whereas in the former Indian model, reactor and gasholder have been separated, the new feature integrated gasholder and reactor into one unit, saving both space and material. Further innovations of this design were the

continuous flow system and automatic overflow when overloading. It was also equipped with a device that should prevent scum to enter the gas pipes. The first unit of this type was installed in 1950 at Osmania University, Hyderabad. The design was called Gramalakshmi; Grama meaning “rural” in Hindi, and Lakshmi is the Goddess of wealth and prosperity in the Hindu religion. There is also a notion of the word Grama toward the Gandhian movement of rural development.

The work of Mr. Patel continued during the 1950s; other institutions such as the Rama Krishna Mission in Calcutta and Khadi Pratisthan Sodepur in West Bengal did also develop new designs. A number of pilot units were constructed especially in the regions of Maharashtra and in the vicinity of Delhi. KVIC included dissemination of biogas technology in its rural development program since 1961, as a result of the earlier field trials. The Planning Research and Action Division (PRAD) of Uttar Pradesh took further national initiatives by establishing a research station in Ajitmal. This research station later became known as the Gobar Gas Research Station, and one of the influential persons was Mr. Ram Bux Singh. Until 1974, about 6,000 biogas units were set up in India.

In 1975, the years following the worldwide energy crisis, it was considered that a well-tested low-tech biogas technology existed, and the required infrastructure for carrying out a nationwide dissemination program was planned, with the aim to install 1.5 million biogas units by 2001. Many organizations and institutions were involved, but the main responsibility for the implementation of the program was held by KVIC. The biogas program was in many respects in line with the development goals defined by Indira Gandhi and the government. The technology was indigenously Indian; it was expected to develop the rural areas and to improve the livelihoods of rural population. It was also a response to the increased oil import expenditures India had experienced some years ago. Identifying the fuel wood crisis, biogas technology was considered, among many planners and policy makers, to be a real solution to the problem. International organizations and donors were beginning to show interest in the technology. Rural development and appropriate technology were attractive for any development program. Small-scale technologies were given attention as

possible solutions to the limits of finite resources. It was considered that the dissemination of biogas technology was a potential way to improving the situation for rural people with limited budgets. In 1978, the Gobar Gas Research Station in Ajitmal, Uttar Pradesh, came up with a prototype of a new design called Janata biogas plant, meaning “public” or “people” in Hindi. The Janata design was similar in several ways to the Chinese fixed-dome design, but with one notable difference: The Janata design was not equipped with a manhole on the top of the digester, which was a common feature of Chinese designs. The (Chinese) manhole or the floating gas drum on the top made it possible to use other feedstock than manure, as feedstock that floated on top of the slurry could be taken out. Floating biomass can cause blockage of gas pipes as well as the digester volume is not used efficiently with reduced gas production as a result. Therefore, the main advantage of the Janata type over the KVIC design was the reduced cost for construction. By 1980, approximately 90,000 low-tech rural biogas units had been installed in India of which only a small number were of the Janata type.

The Government of India launched in the years 1981/1982 an extension and development program called National Programme for Biogas Development (NPBD). The Ministry of Agriculture was only to implement the program. NPBD still exists and the goal, as it is presented today, is: *...providing clean and cheap source of energy in rural areas, producing enriched organic manure for supplementing the use of chemical fertilizers, improving sanitation and hygiene and removing drudgery of women* (MNES 1996).

In 1984, the NGO Action for Food Production (AFPRO) introduced their new biogas design called *Deenbandhu* biogas plant meaning “friend of the poor” in Hindi. This design was approved for inclusion in the NPBD in July 1986. The *Deenbandhu* design was claimed to further cut the cost of biogas installations. Actually it was not a really new design, but rather a further development of the Janata type. The cost reduction was due to the use of some standardized pipes and a different construction technique. The design soon became the most popular design within the NPBD.

In 1996, there were a total of seven biogas plant designs approved by the Ministry of Non-conventional

Energy Sources (MNES). Besides the Khadi and Village Industries Commission (KVIC), Janata, and Deenbandhu, there were the Pragrati design, KVIC design with reinforced plastic dome (composite), KVIC design with ferro-cement dome, and the FLEXI-design (rubber based).

Since 2002, national dissemination speed achieved about 1.2 million biogas plants per year, rising from 100,000 units yearly before. Today basically one design, the Deenbandhu, is disseminated throughout the whole country, thus following a “one design fits all” approach.

Nepal Biogas in Nepal can look back on a long, eventful history. The Belgian Reverend Saubolle first introduced it on an experimental basis in 1955. Subsequently, several organizations became involved in promoting the technology. His Majesty's Government of Nepal launched the first official biogas program in 1974. Under this program, the Agricultural Development Bank of Nepal offered construction loans to potential customers. In 1977, the Government established the Biogas and Agricultural Equipment Pvt. Ltd. popularly known as Gobar Gas Company (GGC). This state-owned entity was in charge of the development and promotion of large-scale dissemination of biogas technology in Nepal.

Started in the 1980s as a technological research project with a limited number of test models, it was expanded during the 1990s by the Biogas Support Program into a successful market development program with the active involvement of the private sector and business community. Over the last 20 years, more than 200,000 biogas installations have been built and the sector now comprises more than 70 local companies and employs about 11,000 people.

Pakistan The history of biogas technology in Pakistan started 1974. Around 6,000 mainly small 6 m³ scale digesters have been installed across the country till the end of 2006 – against the technical potential of about five million digesters based on its suitable climate and availability of cattle dung as feedstock.

The Government of Pakistan started a comprehensive biogas scheme in 1974, and commissioned 4,137 household biogas units by 1987 throughout the country. These were metal floating-drum biogas plants with

a capacity varying from 5 to 15 m³ biogas productions per day. This program was implemented in three phases. During the first phase, 100 demonstration units were installed under grant by the government. During the second phase, the cost of biogas plants was shared between the beneficiaries and the government. In the third phase, the government withdrew financial support for the biogas plants, although technical support continued to be provided free of cost. Unfortunately, after the withdrawal of the government financial support, the project did not progress any further.

The Pakistan Centre for Renewable Energy Technologies (PCRET) started the fourth biogas phase in early 1997 with the installation of 4,000 household plants in several major cities of the country, having a digester volume between 5 and 15 m³ biogas productions per day. PCRET disseminated small-scale biogas technology and has supported installation of around 1,600 biogas plants in 2006. In addition, PCRET had plans to install 2,500 plants by 2008 for which the Government of Pakistan had approved financial support. Three community size biogas plants have been installed in rural areas of Islamabad, which are meeting domestic fuel needs of 20 houses.

The NGO Initiative for Rural and Sustainable Development (IRSD) has installed around 150 biogas plants with support from the United Nations Development Programme (UNDP) Small Grants Program. Some Regional Support Programs and NGOs have also included biogas among their projects: “Koshis” in Sialkot, Punjab, helped villagers to build over 200 biogas plants; “Green Circle Organization” is building community-based plants with funding from the Pakistan Poverty Alleviation Fund. Most NGOs received technical assistance from PCRET in the design of their plants. With some exceptions most plants are still installed on a pilot basis and have not been promoted commercially to any large scale. During the years 2005/2006, the Alternate Energy Development Board (AEDB) installed 1,200 family-size biogas plants to cover fuel needs of 1,200 households in the rural area of the Punjab province.

Most of the biogas plants installed in recent years were smaller household designs with 3–5 m³ gas production per day, compared to the larger plants constructed in the 1970s and 1980s. The biogas technology most commonly used in Pakistan is the

floating-drum design. The Chinese fixed-dome design was installed on a pilot basis but was reported not to be successful. Obviously due to poor construction quality, the Chinese dome design pilot biogas plants showed persistent leakage and seepage problems, and therefore, the gas pressure was reported to be low. Twelve fixed-dome “Nepalese design” biogas plants of Model GGC 2047 of 6 m³ were installed in the “*tehsil*” (sub-division) Pasrur of Sialkot District in partnership with the Punjab Rural Support Program (PRSP) and four plants of the same design were installed in different sizes of 8 m³ (2 units), 20 m³, and 35 m³ in Dera Ismail Khan in partnership with the Foundation for Integrated Development Action (FIDA) by the Rural Support Program-Network (RSPN) in June of 2007. FIDA was reported to have plans to continue supports to install biogas plants in its working areas. In 2006 SNV started to support a new nationwide biogas dissemination program for low-tech household biogas digester systems.

During 2002, a more efficient and cheaper “Thailand model” of a household biogas plant was installed at the Green Circle Organization (GCO) working model site to compare efficiency and cost-effectiveness of two models, the Thai and the formerly applied one. Transfer of the new Thai biogas technology and dissemination of information started in the Village Shirin Muaafe, *tehsil* Depalpur of Okara District. The results are that due to the proper dissemination of information, GCO have facilitated the farmers to install 80 biogas plants in the vicinity of the project area.

A governmental supported project on White Revolution “Dhoodh Darya” started in 2009 with 10 components with main thrust on development of milk pockets and establishment of milk pasteurization plants, infrastructure development of military dairy farms, bulk vending of milk, training and extension of Pakistan Dairy Development Company’s (PDDC) breeding program, and promotion of biogas units. It has already developed 48 community farms, trained a large number of farmers, and installed 825 medium-sized biogas units. The work started in the year 2009 for the establishment of community farms, biogas plants, large and small pasteurization plants, and bulk vending units, and training of master trainers will be continued up to the end of 2011.

Philippines Dr. Felix C. Maramba, an agricultural engineer by profession of the then Araneta University Foundation, introduced biogas technology in 1965. The today De La Salle Araneta University (DLSAU) was formerly known as the Gregorio Araneta University Foundation, which was established in 1946 as the Araneta Institute of Agriculture. The university specializes in Veterinary Medicine and Agricultural Sciences. He is the founder of the Maya Farm Biogas Model. In the early 1970s, the Maya Farm, a commercial piggery farm located 40 km east of Manila, has been the pioneer in the development of biogas technology. In order to obtain the necessary experience and to assess the suitability of different types of plants, demonstration models of Indian, Chinese, and European types were set up. The models were later modified and used as pilot plants. Biogas produced at the farm supplies 40% of the total power requirement of the farm and is used for home applications, cooking vats in the canning plant, fuelling of burners for heating and gasoline engines, running a feed mill, operating a 60 kVA electric generator and running farm vehicles. The organizations engaged in extension of biogas technology are the National Housing Authority, the Engineering Battalion of the Military, and the Department of Community Development. The Development Bank of the Philippine granted loans to farmers at low interest rates for the biogas project.

The Philippine NGO Rural Life Centre (PRLC) promoted a culvert-type biogas system in the early 1980s. The PRLC trains people from the government as well as from the private sector in the field of animal production and biogas technology. Many units of the model were copied and installed in selected villages but the continuity ceased because the PRLC project was terminated in the late 1980s.

The Philippine National Biogas Technology Extension Program in Key Livestock Areas was established in 1996 in cooperation with the Department of Energy and the Department of Agriculture where Cavite State University was designated as the National Biogas Centre. Since then, a number of local, regional, and national seminars, trainings, and workshops were conducted to promote the technology. Participants came from various sectors of the society: private individuals, companies, NGOs, agro-industry, and government agencies.

The Philippine Agricultural Engineering Standard PAES 413:2001 about Agricultural Structures–Biogas Plant was initiated by the Agricultural Machinery Testing and Evaluation Centre (AMTEC) under the project entitled “Enhancing the Implementation of Improved Agricultural Engineering Standards” which was funded by the Bureau of Agricultural Research (BAR) of the Department of Agriculture (DA).

Thailand Thailand was introduced to the biogas technology in 1950 by Kasetsart University (KU), which continues to be a cooperating agency even today. In 1960, due to poor hygiene and the need to improve health conditions in rural areas, the Department of Health (DoH) within the Ministry of Health (Sanitation Division) became involved, promoting biogas tanks as a sanitation technology.

The need to conserve energy dominated during the first and second oil crises between 1970 and 1980. It was then that the National Energy Administration (NEA) and the Department of Agricultural Extension (DoAE) started to introduce biogas programs for rural energy on small farms. By 1988, about 5,500 biogas plants were constructed, those being mainly 4 and 6 m³. In order to overcome the numerous technical and managerial uncertainties, an improved Biogas Programme in Thailand was implemented in September 1988. Responsibilities for carrying out its activities were with the Chiang Mai University (CMU) and with the Department of Agricultural Extension (DoAE) within the Ministry of Agriculture and Cooperatives. The German Development cooperation supported the program from September 1988 until December 1994 (Thai-German Biogas Programme). Several systems of all sizes have been constructed in the northern and western regions of Thailand, partly supported through loans from the Bank of Agriculture and Agricultural Cooperatives (BAAC) in Thailand.

Biogas Advisory Unit (BAU) at Chiang Mai University, with a grant supported by the government under The National Energy Policy Office (NEPO), launched the National Biogas Dissemination Program for the medium and large-scale livestock farms in October 1995. A target of 50,000 m³ biogas system within 6 years, starting from 3,000 and 7,000 m³ in the first and the second year, with another 10,000 m³ annually in the following years, is the goal of the program. The

program concept consists of two major parts: (1) the dissemination of small household biogas digesters (8, 12, 16, 30, and 50 m³ volume) under the responsibility of the Department of Agricultural Extension (DoAE) within the Ministry of Agriculture and Cooperatives and (2) applied research and development at CMU, including the provision of consultancy services for anaerobic wastewater treatment to specialized pig farms.

From 1995 until 2000, 70,000 m³ volumes of digesters had been built with support through the Energy Conservation Fund under the National Energy Policy Office (NEPO) in Thailand. The Energy Conservation Fund (through the Renewable Energy Programme) aims to provide financial incentives, as well as awareness campaigns, in order to promote the generation of methane gas from agricultural wastes. Only a few provinces with a high potential for biogas utilization (i.e., high concentration of suitable animal farms) will be selected for this program. Since 2001 the implementation was fully transferred to the responsibility of private contractors, as a regular business sphere in the field of environment protection (“commercialization” of the technology).

Vietnam Biogas technology has been introduced and developed in Vietnam since 1960. The history of biogas technology began in the South; the Department of Animal Husbandry conducted research on collecting methane gas from animal manure.

In the northern part of the country, biogas technology was introduced in 1964, when the Ministry of Industry started the first “Methane power station” in Bac Thai province. Between 1965 and 1975, Ha Noi, Ha Nam Ninh, and Hai Hung provinces also built biogas plants. These plants stopped functioning after a short time due to a lack of access to technology and management experience.

After the country’s reunification in 1975, it was one of the top priorities of the state research program on new and renewable energy until 1990. Within the framework of this program, there were many research projects focusing on biogas technology. The institutions participating in the program were the Institute of Energy, Technology University of Hanoi, Technology University of Ho Chi Minh city, Technology University of Da Nang, Can Tho University, and provincial

departments of Science, Technology and Environment. In 1976, the Vietnam Institute of Energy began researching “Fermentation for methane gas production.” From 1981 to 1990, there was renewed interest in biogas technology with the introduction of the National Research Program on New Energy Sources within the Institute of Electricity Science and Technology and international support from the Soviet Union, OXFAM UK, UNICEF, Sweden, and others. Institutes, research centers, colleges, army units, and individuals collaborated on biogas projects.

By 1990, about 2,000 small biogas units had been built in Vietnam with size ranging from 3 to 10 m³. Some of the most common types of biogas plants used in Vietnam include floating gas holding units, biogas units with plastic bags; fixed-dome brick biogas plants some with composite cover, spherical form digesters, Energy Institute type NL6 digesters, and household models KT1, KT2, and KT2B. In general, while all biogas technologies have advantages and disadvantages, biogas is the most suitable technology for livestock waste treatment. The first national workshop on biogas was organized within the frame of the National Program on New Energy Source. This workshop helped build momentum to advance research and development of methane gas and biogas technology in Vietnam. From 1991 to 2001, biogas technology developed rapidly with continued support from the Vietnamese government and international partners.

Since 1992, within the framework of the projects of the Ministry of Agriculture and Rural Development of Vietnam (MARD), polyethylene plastic bag digesters have been developed. Owing to low cost and simplicity of installation, this technology has been rapidly adopted and disseminated by the network of Agricultural and Forestry Extension, Association of Vietnam Gardeners (VACVINA), and some local private actors. It is estimated that up to one million of such simple very low-tech plastic bag digesters may exist today.

By the end of the 1990s, the Centre for Rural Communities Research and Development (CCRD) further developed the original model and has successfully designed and introduced a new advanced biogas model, named “Hybrid Technology Bio-digester with Automatic Scum Control” or VACVINA Bio-digester, in order to help farmers to apply biogas technology, generate biogas for cooking, reduce workload for

women, actively treat waste from livestock, protect the environment, and reduce pressure on forests. In 2000, the Toyota Foundation provided support to enhance capacity building of VACVINA’s staff and to disseminate the VACVINA biogas model nationwide. More than 300 technicians had been trained on all necessary skills on building VACVINA bio-digesters and more than 750 biogas demonstration models have been built in the 61 provinces of the country. In conjunction with CCRD, from 2006 to 2009, ETC Foundation (Netherlands) and Research Centre for Energy and Environment (RCEE) started a development strategy for Enabling Access to Sustainable Energy, including the VACVINA biogas model in a market orientation approach in Thanh Hoa province. In 2011, there are more than 11,000 VACVINA biogas plants constructed by farmers themselves with technical assistance of trained technicians. MARD in Decision Nr.4414/QĐD-BNN-KHCN of October 18, 2002 recognized this initiative and allowed its application nationwide.

Also in 2002, MARD issued standards for small-scale biogas systems (10TCN 492÷499-2002 and 10TCN 97÷102-2006). In 2003, the “Support Project to the Biogas Program for the Animal Husbandry Sector in Some Provinces of Vietnam” has been initiated. The goal of this project was to develop a commercially viable and market-oriented biogas industry and contribute to avoiding the use of fossil fuels and biomass resource depletion. The Department of Livestock Production, MARD, and the Netherlands Development Organisation (SNV) are the primary implementing agencies for the project. By the end of 2008, the program provided training for 500 provincial and district technicians, 700 biogas mason teams, and organized thousands of promotion workshops and trainings for biogas users. By the end of 2009, the project has supported construction of over 78,480 biogas plants and received recognition for its efforts by winning the Ashden Energy Award. The project aims to develop around 167,000 low-tech biogas projects in 63 provinces throughout Vietnam by end 2012.

Under the World Bank funded and MARD implemented Livestock Competitiveness and Food Safety Project (LIFSAP) there is also a small household biogas component, running from 2010 to 2014. The project supports up to 12 provinces which will meet the eligible criteria established by MARD,

including: (1) the density of livestock farms and livestock populations, (2) livestock market share, (3) the availability of livestock support infrastructure, and (4) a viable policy to support the development of livestock production. The total grant amount per biogas plant is US\$ 200 to support both the construction of the biogas plant and for additional bio-security measures. Without taking into account program costs the funding will be enough to support the construction of a maximum of 20,600 biogas plants.

In addition, the Asian Development Bank loan financed “Quality and Safety Enhancement of Agricultural Products and Biogas Development Project” (QSEAP) commenced in 2010 and will end in June 2015 and covers 16 provinces in the country. The project’s purpose is to build 40,000 biogas plants with the provision of subsidy to at least 20,000 households, and credit to households and farms raising animals. Up to now, the project team received initial results: training 276 technicians, 359 skill masons, and constructing 6,953 biogas plants of small scale of model KT1 and KT2 in 16 provinces.

Parallel to the agricultural-dominated biogas activities, the National Rural Clean Water Supply and Environmental Sanitation Program is targeting to promote the construction of 1,000,000 household biogas-sanitation plants or at least toilet connection to existing agricultural biogas plants in the period 2000–2020.

Africa

The first aid-driven approach for biogas extension in Africa dates back to the early 1970s, when politicians and decision makers from different African countries visited India and were fascinated by the biogas technology. The Indian Government, and later also the Chinese Government, showcased their specific biogas technologies in different African countries in such a way that a foreign expert team built a few institutional biogas digesters and trained numerous people in design and construction only. As no funds have been made available for long-term commitment and dissemination programs, these approaches led to failures in operation, management, and even construction copies, which are scattered all over the continent, particularly in agricultural institutions. At this time, the main actors in potential biogas dissemination programs

were identified in the governmental agricultural or energy research institutions of the respective countries. But a deeper rooted operational and managerial know-how or commitment could not be developed or conserved.

In the late 1970s, triggered by Ernst Friedrich Schumacher’s (1911–1977) “Small is Beautiful” (first published in 1973) appropriate, simple technologies entered the arena of development work in the South. Not northern high-tech, but innovative, affordable, simple, and traditional technologies were believed to be the remedy for the development and technology gap between industrialized and developing countries. This resulted in a cross-sectorial scheme of many development cooperation institutions accompanying and supporting the development and dissemination of biogas technology in Latin America, Asia, and Africa. Industrialized countries neither had sufficient experience nor appropriate technologies to build on in developing countries. Rather, this experience was identified in India and China and became an issue for a South-North-South transfer.

In 1980, the German Federal Ministry for Economic Cooperation (BMZ) instituted a “Biogas Extension Programme” (1980–1993) as part of the German development aid. It was prompted by the realization, and by analyzing the results of the first German development supported biogas projects in Cameroon in 1978, and short-term consulting work done between 1977 and 1980 in India and China, that biogas extension requires an integrated approach. After understanding the reasons for the failures in the past, it was realized that compromises in technology quality could not be accepted. Only proven designs with good building material were used. Piping was changed to galvanized steel or HDPE pipes only, instead of garden hoses and gate valves, which both leak after a short time.

Prepared in October 2005 in Beijing as a Chinese-Netherlands-German effort, and based on the success in some Asian countries, in May 2007, representatives from 27 African countries met in Nairobi, Kenya, to formally launch the “Biogas for Better Life Initiative.” Since then, a number of country biogas program pre-feasibility and feasibility studies have been completed by the Netherlands Development Organization (SNV) and the German International Cooperation (GIZ), and programs are already being launched in Rwanda,

Uganda, Burkina Faso, Senegal, South Africa and Ethiopia. The group discussed important aspects of developing and implementing national biogas programs including sanitation, gender integration, technology, costs, program structure and management, financing and subsidy structure, carbon financing, and marketing and communications.

A Foundation “Biogas for Better Life: An African Initiative” has been established on February 28, 2008, in the Netherlands to provide this initiative with a legal basis. This allows the initiative to sign agreements with sponsors to support the initiative financially; to enter into agreements for the implementation of national biogas programs, such as the one for Rwanda; to support research and development and knowledge management in biogas; and support all the components of the Initiative Business Plan 2006 till 2020. Until recently, this was done on an individual and ad-hoc basis with individual sponsors such as Shell Foundation, International Humanist Institute for Cooperation with Developing Countries (HIVOS), German International Cooperation (GIZ), the Netherlands Development Organization (SNV), Dutch Ministry of Foreign Affairs (DGIS), Practical Action, German Bank for Reconstruction and Development (KfW), and many others.

Today, “Biogas for Better Life” is an African initiative that aims to improve the health and living conditions of men, women and children; to reduce the use of firewood and charcoal for cooking; to improve soil fertility and agricultural production; to reduce greenhouse gas emissions; and to create new jobs through the development of a robust biogas-related business sector throughout the African continent.

The initiative will identify “pockets of opportunity,” and initially focus on programs in African countries with the strongest market potential. The initiative aims to install two million household-level biogas plants in 10 years. The ultimate objective is to develop a sustainable, commercial biogas sector, which will in turn improve the lives and livelihoods of families in Africa. The initiative will foster partnerships and knowledge exchange, provide leadership and experience to developing and implementing national programs, stimulate further technology and market-based research, and help identify and develop financial resources for the biogas programs. Further extension is

planned soon to Kenya, Mali, Zambia, Niger, Ghana, Malawi, Lesotho – where biogas technology is already successfully disseminated since 2003, namely, Swaziland, Sudan, and the West African countries.

Algeria French researchers in North Africa, between the years 1940 and 1951, are reported to have made extensive efforts to develop so-called dry-fermentation methane digesters based on straw and manure. There is ample literature on their work in French journals. G. Ducellier and M. Isman developed the design and prototypes in the then French North Africa already as early as 1937. The technique of Ducellier and Isman, at the Institute of Agriculture in Algeria, was the first ever batch-fermentation system with pre-aerating (pre-composting) of the waste mass (straw-manure-organic waste) for 20 hours in order to raise the temperature to 70–80°C. The wastes were then flooded with water and liquid manure, and the anaerobic process commenced. A floating gasholder covered the tank and straw had been packed to a thickness of 40 cm out around the walls to serve as insulation. In unmixed tanks of several 10 of m³ of size the biogas production was 70–90 m³/t wastes capacity, averaging 0.4 m³ per tank volumes/day for the duration of the fermentation.

Burundi The first national biogas program, started in 1984, was supported by German Development Cooperation (GIZ) and established in cooperation with a Belgium research project and a Chinese training program for biogas constructors, using livestock manure, toilet wastewater, and human excreta as feedstock. A countrywide biogas school sanitation project with World Bank support was carried out from 1985 to 1989 led by the Ministry for Energy and Mining. Several projects were initiated by the GIZ Biogas Dissemination Programme, which started in 1984 in the eastern region of Cankuzo. In 1988, this project was integrated into the “Special Energy Programme” and was stopped due to civil war in 1992.

After first experiences with family-sized biogas plants, the project team started in 1987 to build medium-scale biogas-sanitation systems (100–250 m³) to treat human excreta and gray water of boarding schools. Private contractors were responsible for the plants. The training of craftsmen, the establishment of a service system, and the setup of material credit funds

were to provide the basis for a self-reliant dissemination concept. By 1992, 206 small-scale biogas plants, and 84 institutional medium-scale biogas-sanitation plants (tunnel and fixed-dome plants) had been constructed. Six out of ten households examined under the Biogas Survey in 1992 used liquid slurry as fertilizer. Learning from Burundi, biogas units were also constructed in Bukavu/Congo.

Ethiopia Biogas technology was introduced to Ethiopia in 1977 through the German NGO Bremen Overseas Research and Development Association (BORDA) with German development cooperation support. In the years 1986 to 1988 in 21 counties (Woredas) west of the Amhara State, Indian design floating-drum plants with a volume of up to 8 m³ have been financed and built by the Rural Technology Promotion Centre Bahir Dar. In a bilateral project, German development cooperation supported the construction of 120 biogas plants between 1999 and 2002 by informal private firms and the local NGOs.

Since 2008, the Netherlands Development Organisation (SNV) supported a pilot phase of a National Biogas Program Ethiopia (NBPE) aiming to build within 5 years up to 14,000 low-tech fixed-dome biogas plants in four regional states. It is expected to develop a private and competition-based biogas industry. The NBPE promotes only plants of 4, 6, 8, or 10 m³, thus limiting subsidies to farms with a maximum of 100-kg manure per day, corresponding to approximately 20 local cattle.

Kenya First attempts to use biogas technology to obtain energy from coffee pulp go back to the mid-1950s. In the following 25 years, the private entrepreneur Hutchinson sold more than 100 plants of various types mainly to large-scale farmers. In 1983/1984, Germany supported the training of craftsmen in the construction of biogas plants; as a result, 40 biogas plants were built in the Meru region. Until 1988, extension of dissemination efforts into other regions led to about 250 floating-drum plants in various regions, mainly for energy supply. Following the philosophy that an extensive project apparatus with a solid financial background has time limitations, emphasis was placed from the very beginning on private entrepreneurs for the construction of the plants and the

provision of biogas accessories. Only demonstration plants in new project areas were subsidized by the project; in other cases, biogas customer pays the market price for his plant.

From 2006 until June 2011 with funding from the European Union dissemination measures for resource-friendly technologies succeeded in the installation of more than 200 low-tech biogas plants. Since 2003, and jointly coordinated in one program, Germany and the Netherlands are supporting the integrated biogas development in the agricultural sector. A national biogas technology standard is under preparation since 2011.

Lesotho Since 2003, after Food and Agriculture Organization of the United Nations (FAO) and China supported pilot experiences during the 1980s, a digester design that has undergone various adaptations in African countries under the umbrella of the German Development Cooperation (GIZ) has been implemented in Lesotho by a newly launched NGO, Technologies for Economic Development (TED). Since then, it is widely proven that biogas technology can work successfully in the Mountain Kingdom.

TED was created as a successor of the *Lesotho Biogas Technicians Self Help Group*. With the TED design, incorporating household wastewater into the feeding material for anaerobic digestion, a solution for the most pressing problems especially for urban households was identified: lack of water for irrigation, expenses for construction, and maintenance of septic tanks.

In cooperation with TED, more than 300 digesters of varying sizes were built and most of them are still in operation. The TED bio-digester works well on household, institutional and settlement level as well as for an industrial abattoir with its special feedstock. Today, biogas in Lesotho is a technological package where wastewater and other organic matter are treated in a bio-digester producing gas as an energy source and water is further purified as fertilizer or sludge as soil conditioner or fertilizer. The technology follows the concept of DEWATS (Decentralised Wastewater Treatment Systems) as developed by BORDA (Bremen Overseas Research and Development Association), however, with special focus on energy generation that substitutes up to 20% of a household's cooking fuel demand.

The system is found appropriate not only for the capital Maseru and the district towns as many households and institutions have serious problems, and high cost burden with the disposal of their sewage; the TED system does not cater only for water-borne sanitation but also for dry systems. Peri-urban farms start nowadays to be interested in the system, too. TED provides 12 months after-sales service free of charge, a paid life-long after-sales service, and trains owners on how to care for the system. Currently, about 25 units are constructed per year, totally financed by the individual clients.

Morocco The dissemination of biogas technology focused on the Souss-Massa region. Initially three fixed-dome plants were rehabilitated, and three 12 m³ plants, five 20 m³ plants, and two 85 m³ plants were constructed with the main purpose of electricity generation. By 1998, 80 digesters have been installed (10–100 m³) with a total volume of 2,000 m³.

In 1995, a biogas plant was constructed at the wastewater treatment plant in Ben Sergao to use sewage sludge for biogas production. Since 2008, German Development Cooperation (GIZ) started to support low-tech biogas installations for wastewater and manure treatment.

Tanzania The history of biogas dissemination in Tanzania dates back to 1975 when the Small Industries Development Organisation (SIDO) built 120 floating-drum biogas installations up to 1984. In 1982, the newly created Centre for Agricultural Mechanization and Rural Technology (CAMARTEC) took over the promotion of biogas in the Arusha area. In 1983, German Development Cooperation (GIZ) introduced a biogas extension service and disseminated biogas plants mainly in this region where favorable agricultural and socioeconomic conditions let expect a high dissemination for biogas plants. The project worked with a standardized plant design, clearly defined administrative procedures, and offered a warranty of 2 years and technical advice to the users in the villages. In 1984/1985, household biogas plants were offered with digester volumes of 8, 12, and 16 m³, and in 1990, the program included standardized plants of 12, 16, 30, and 50 m³ for households and institutions as well as a special “toilet biogas plant” for institutions.

Request which could not be covered by the standardized range of plants and services and which required additional research and development work had to be financed completely by the customer. The program introduced the *biogas unit concept* defining the *unit* as (1) an appropriate stable with solid floor, (2) a pressure tested piping system, (3) gas use appliances, and (4) a slurry utilization system adequate to the individual farm. The costs for a biogas unit increased from around TSh 300,000 in 1989 to TSh 400,000 to 7,000,000 in the beginning of the 1990s. Despite this, the number of units constructed until 1992 increased to about 400. Between 1990 and 1993 CAMARTEC conducted four international training courses with national and international participants and trainers, leading to the popularization of the CAMARTEC design in Ethiopia, Kenya, Uganda, and Thailand.

The dissemination strategy and project structures underwent decisive changes around 1990 as a result of transfer of the project to the counterpart organization. German experts also studied large-scale application of industrial biogas units for sisal industry; the first unit in Tanzania was constructed in 2007 by a Chinese-German consortium supported by the United Nations Industrial Development Organization. Since 2008 Tanzania established a nationwide new biogas dissemination program with SNV support.

Tunisia Biogas was introduced in the Sejenane region in 1982 as an 11 m floating-drum plant. In 1986, the first fixed-dome plant (6 m³) was built. With German Development Cooperation (GIZ) support, in 1989, non-functioning plants in the region were rehabilitated and 10 new plants built. The first technicians received training in Burundi and Germany. A biogas laboratory was installed at the Technical University Tunis in the framework of German Development Cooperation (GIZ). The activities focused on the modification of the technical aspects (mainly gas appliances), training measures, and slurry experiments under local conditions. Between 1990 and 1992, 16 more biogas plants were constructed. The first solar-heated low-tech fixed dome digester was reported to be operated by the Technical University Tunis. Then China took over the activities, supporting Tunisia until 2003 with the training of biogas technicians and supporting some more

biogas plant construction. Since 2011, World Bank is strongly supporting the new biogas development for large dairy farms in Tunisia.

Rwanda In Rwanda, biogas technology is quickly catching up through the efforts of Kigali Institute of Science Technology and Management (KIST), where several former counterparts of the Germany supported Project in Tanzania (with CAMARTEC) are working. KIST has designed and built a 150 m³ fixed-dome digester in Cyangugu prison that is fed with waste generated by 1,500 prisoners. This digester produces methane gas that caters for 50% of the cooking needs for the 6,000 inmates. KIST has also solved the sewerage and hygiene problem at the school “Lysee de Kigali” by providing a 25 m³ fixed-dome digester connected to six bio-latrines. The biogas produced is used as cooking fuel for 400 students and for operating Bunsen burners in the school laboratories. KIST was also supported for many years by Chinese experts to introduce biogas digester design-based decentralized wastewater treatment systems (DEWATS). Since 2007, Rwanda established a SNV-supported National Biogas Program with the target of 14,000 plants in 5 years. China is once more engaged in the Rwandan biogas sector since 2009, and has promoted since then at least 100 prefabricated composite biogas plants, which had been delivered from China.

Central and South America

In Central and South America, biogas plays a role within the renewable energy sector, too, although many countries are still missing in the list of advanced renewable energy technologies and dissemination.

Belize The first project in biogas technology started in 1988. It evolved from a Caribbean biogas dissemination program carried out by the Caribbean Development Bank. German and local biogas consultants and biogas technicians have been active in the region constructing three floating-drum plants following the BORDA model within the Caribbean Technology Consultancy Services (CTCS). As neither the market forces could take up biogas technology nor could independent dissemination structures grow, the program continued in 1989 along the lines of experience gained

during biogas activities in the Caribbean and Nicaragua – to anchor biogas-specific, national know-how in a local and regional dissemination structure. With this background experience and the financial, personnel, and material support of the Caribbean Biogas Dissemination Program, a German integrated expert under local project contract and a Belizean expert have been employed to build up such a structure in cooperation with the state Central Farm and to demonstrate the high performance and efficiency of biogas technology. In 1991 the CAMARTEC model from Tanzania was introduced. In comparison to the high input of material and work in plants used previously (reinforced steel vault and fundament), a cost reduction of approximately 15–20% was achieved. Since 1993, at least 20 plants have been built (of these, five are constructed at institutions, 13 at household, and two are medium-sized farm biogas plants). The target group for the household biogas plants so far consisted of farmers involved in commercial pig production. Low-tech household biogas system users in Belize mostly own 5–40 pigs.

Nowadays, with support of the European Community and through the partnership with the Ministry of Agriculture and Fisheries (MAF), the Inter-American Institute for Cooperation on Agriculture (IICA) and the Belize Audubon Society (BAS), small- and medium-sized farms are benefitting from biogas installations as a low-cost alternative and renewable energy source.

The first phase of biogas digester implementation was initiated by a “training the trainer” course conducted by the EARTH University in Costa Rica. This training received a follow-up by means of the installation of biogas digesters at Central Farm and Yo Creek Agricultural Stations, San Antonio and San Marcos in the Cayo district, Maskall and Crooked Tree in the Belize district, and San Antonio in the Orange Walk district. The promoted low-tech biogas digester (called “the worm”) is a tubular structure made of polyethylene plastic which is placed in a pre-dug pit. The system serves for anaerobic fermentation of organic materials such as manure from pigs, cattle, sheep, and other organic wastes, thus reducing the risk of pollutants and contaminants in the environment. Farmers understand the opportunity to obtain alternative fuel and organic fertilizers, reducing the need for chemical

fertilizers and significantly reducing the cost of production.

The construction of this type of biogas digester is quite simple; it is made of a tubular plastic bag and other basic parts could be found in local hardware and mechanic shops. These basic parts include a few feet of PVC pipes, a few elbows and connections, used bicycle tubes and recycled buckets.

Bolivia In 1986, the GIZ started as project in cooperation with the Universidad Mayor de San Simon (UMSS) in Cochabamba to disseminate biogas technology. Until 1989 these activities were part of the supra-regional GIZ Biogas Dissemination Programme. From January 1990 to the end of 1992, the biogas activities were continued as a component of the Bolivia Special Energy Program. By consolidating biogas technology into the Cochabamba Department and into the general background of national energy and landscape planning by means of the National Biogas Network, the aim was to integrate “biogas technology into the agricultural production process” so that the “destruction of agricultural ecosystems” could be curbed and “energy and organic fertilizer” could be produced in a decentralized manner. A total of 27 plants, nine of them in the Cochabamba area, have been constructed by different organizations already before the German support started.

In 1988, the German Development Cooperation (GIZ) purpose was defined as “the creation of fundamentals on which Bolivian institutions will be enabled to disseminate biogas technology extensively through training and construction of demonstration plants.” Loans, training, and the improvement of project management were to allow a high-performance dissemination structure. Emphasis was given to the integration of the technology into local, regional, and national socio-economic structures and on the dissemination of “Integrated Farming Systems.” The biogas plants were mainly understood as “fertilizer-producing plants” making a significant contribution to the strengthening of intensive animal husbandry and agricultural production.

After constructing the first four solar-heated biogas plants in the 1980s in the Bolivian highlands at 4,000 m altitude, the project regions of higher altitude were declared unsuitable for low cost, but not for low-tech

biogas plant dissemination. Therefore the biogas office concentrated more and more on the migration regions in the tropics with an inferior infrastructure. In these regions about 35 plants were built between 1989 and 1992. A survey carried out by the biogas office has identified potential, particularly in the area of Santa Cruz de la Sierra, in the field of industrial and communal sanitation. After having built a UASB (up-flow anaerobic sludge blanket) digester at the Palmasola prison, knowledge about anaerobic wastewater treatment technology was established in local NGOs, supported by integrated experts from Germany.

As Bolivian NGOs continued with successful biogas extension of 250 PVC-plastic plants from 2002 to 2005 in high altitudes, in a second attempt by German and Netherland development support, a new program was launched in September 2005 with the goal to supply 575,000 people, corresponding to 6% of the Bolivian population, with modern renewable energy. Donors like the World Bank, International Fund for Agricultural Development (IFAD), and the Inter-American Development Bank (IADB) evinced interest to participate in this program. With the approach of process consulting and human presence on the ground, the German Development Cooperation (GIZ) took an important role as adviser of the national biogas program.

Since 2007 about 250 low-tech and low-cost PVC-plastic bag sausage-shaped biogas plants of 8 m³ have been disseminated in Alti-Plano villages at 4,000 m and in the temperate area of Cochabamba. Packed in earth wall bricks and covered with straw roofs for insulation, they produce enough biogas to provide cooking fuel for 4–5 hours per day. This design receives attention also in the tropical areas and is now promoted as low-tech and low-cost biogas plant.

Columbia In May 1985, the Special Energy Program Columbia located in Barranquilla started. The project concept focused on “investigation of the possibilities of producing and using biogas” in Valle de Cauca. Corporación Autónoma Regional del Cauca (CVC) was the executing organization. A German long-term expert has been integrated into the project from November 1985 to 1992. During the first project phase, the central problem was the pollution of water resources, which should be reduced by the

dissemination of biogas technology. Project activities were characterized by research and development; investigations were carried out on the use of slurry generated in biogas plants. In 1989 the project goal switched to a clear contribution to the improvement of the rural energy situation and the conservation of water resources by the use of biogas plants. This phase was then characterized by rehabilitation of non-functioning biogas plants and the setup of a dissemination structure. The construction of demonstration plants on selected farms aimed at introducing biogas technology in the rural region. Further involvement in the agro-industrial sector was suspended due to the sector's complexity although initial investigations on anaerobic digestion of agro-industrial wastewater had been carried out. Between 1985 and 1992, a total of 25 biogas plants were built, including a floating-drum plant (BORDA type), a tunnel plant, various fixed-dome plants, a balloon plant, and a UASB (up-flow anaerobic sludge blanket) plant.

When the international support came to an end in 1992, standards of biogas plants existed for four fixed-dome plants of 14–48 m³ and three fixed-dome plants of 67–115 m³ with a separate gasholder. In line with the heterogeneity of biogas users' agricultural household and farm systems, the integration of biogas technology into agricultural and farm systems required to be highly flexible. The plants were mainly built for medium-sized and large-scale pig and cattle farms with 20 and 2,000 animals. The heterogeneity of the farms was also reflected in the pattern of utilization and the condition of the plants.

Since 1986, with Belgium and Netherland support, industrial size biogas technology was developed as treatment and reuse system for agro-waste in the tropical regions. During the first years (1986–1989), biogas digesters have been classified as farming intensification technologies. These reactors transformed liquid manure into organic fertilizer; the generated biogas was just a sub-product. This intensification was also applied to the flower agro-business where flower wastes were fed into biogas digesters. Since 1989 anaerobic systems for agro-industries and municipal sewage (UASB technology/anaerobic filter/contact biogas digester/covered anaerobic lagoons) have been built. The biggest municipal wastewater anaerobic treatment plant was installed in Bucaramanga for 100,000 people

equivalent (PE). Since 2005, due to rise of crude oil prices and the implementation of the Kyoto Protocol, activities have shifted toward biogas capture and use.

The low-tech biogas digester technology exists in the country only on small scale, although with a trend to expansion, particularly in suburban areas. Local craftsmen in partnership with NGO have constructed many of these biogas digesters.

Cuba Supported by India, Cuba started its national biogas program in the 1970s; in a second attempt at 1990, biogas was rediscovered with German and Chinese support. Having created a national biogas expert group in Santa Clara in 1994, the current national biogas expert association was formed under the Ministry of Agriculture. Since 1992 international biogas advisers from Germany, Canada, and China have worked with Cuban counterparts supported by Germany, EU, UN-agencies, international NGOs from Canada and the Netherlands, or as part of the Chinese development cooperation with the Ministry of Sugar, the Ministry of Agriculture, and the Ecumenical Council of Cuban Churches. Industrial-sized biogas plants were installed at distilleries, and for sisal and sugar processing wastewater, and for dairy farms and pig breeding farms of about 20,000 animals (e.g., Soroa Farm). In addition to other donors, supported by German, Canadian, and Spanish NGOs, small-scale low-tech biogas digesters, such as fixed-dome plants, floating gasholder plants, tubular PVC and PE bag biogas plant designs, and prefabricated glass-fiber (composite) biogas plants, were jointly developed and locally adapted.

Today (2010) about 1,000 biogas plants are operating throughout the country, mainly low-tech PVC-plastic tubular “sausage” plants and fixed-dome plants; target groups for these plant types are suburban and rural households with pigs, vegetable production, and decentralized small- and medium-scale dairy farms. Biogas is used only for cooking, due to commonly experienced energy shortages. Local institutions nationwide, with an umbrella of a National Biogas Association, are planning to construct yearly about 400 low-tech biogas plants.

Jamaica A document on the Biodigester Septic Tank (BST) was prepared in 2000 by the Scientific Research

Council of Jamaica (Ministry of Land and Environment, 2002) and presented to the Ministry of Commerce and Technology, the Ministry of Health, and the Ministry of Land and Environment/Ministry of Water and Housing for approval to be used as the system for future on-site sewage treatment for housing developments. In the following years a wide range of requests were received from housing developers to utilize the biogas technology which has been developed with German support for the on-site treatment of domestic sewage for urban, suburban, and rural housing, thus replacing septic tanks and soak-away pits.

Nicaragua After a pilot Biogas Dissemination Program supported by the German Development Cooperation (GIZ) in the early 1980s, Stichting Nederlandse Vrijwilligers – Netherlands Development Organization (SNV) restarted pilot activities to prepare a national biogas program in Nicaragua and Honduras in 2010.

Challenges, Success and Failures

Challenges, success and failures of any technology are always linked to a number of factors and influences of quite a variety of characteristics. In the case of “biogas technology,” given that applications occur worldwide under a range of frame conditions that cannot be easily compared, the influencing factors for success and failures are shaped by researchers, housewives, farmers, engineers and technicians, economists and politicians, bankers, energy suppliers, donors, hardware dealers, masons, and plumbers – just to name a few.

Therefore, the following chapter picked one example – the case of a pure market-oriented dissemination approach performed by a non-profit non-governmental organization in Lesotho, southern Africa. The challenges, success, and failures are analyzed against the overall dominating issues of sustainability.

Social and Cultural Sustainability

In order to achieve social and cultural sustainability of the promoted wastewater treatment technology in general and the installed Biogas/DEWATS systems in each specific case, TED, the Lesotho based Non-Governmental Organization “Technologies for Economic Development” applies social marketing principles adapted to sanitation requirements. The

strategy is based on three pillars: (1) stimulating demand, (2) private sector involvement in the supply chain, (3) social status. Following the guideline “Social marketing works to help people change their behaviors positively,” TED engages also in hygiene education, sanitation awareness raising, and sanitation marketing at all levels in Lesotho and abroad.

The creation of a sustainable sanitation market involves five “P”s: (1) product, (2) price, (3) place, (4) promotion, and (5) people, whose quality of life is directly influenced by the improvement of sanitation and hygiene.

Up to now, TED’s Biogas/DEWATS product has several “unique selling points,” as the NGO is still the only national organization to offer a real alternative to a conventional septic tank. Price comparison between the conventional on-site wastewater treatment system and Biogas/DEWATS results currently in lower investment costs for the conventional system, but in significantly lower operational costs for Biogas/DEWATS. Given the specific geophysical context of Maseru and its growth rate into peri-urban hilly areas, the connection to centralized sewer lines and wastewater treatment plants is for most of TED’s clients just not possible.

The sustainable social and cultural integration of TED’s biogas-sanitation system is also enhanced by the strong involvement of the future system owner in the decision on where to place the treatment system for the household’s waste water and the technology choice on reuse options. Also, wherever possible, already existing septic tanks and VIP latrines are integrated into the new design of the treatment system. Due to these close and personal relations with its clients, TED’s promotion strategy relies on “word of mouth” and clients’ testimonies to interested households.

In cases where communities (villages, schools, orphanages) ask for upgraded sanitation systems, TED informs the communities about different options, including urine diversion dry toilets. Urine diversion technologies and Biogas/DEWATS could be successfully combined.

Working closely with local partners at all levels TED spreads the message about the importance of sanitation, hygiene, and water for human well-being to different groups applying appropriate information and

education material. Local authorities, civil society organizations, and media form already part of the still informal sanitation network that TED intends to set up in Lesotho.

Economic and Financial Sustainability

The level of sanitation infrastructure in Lesotho is generally very low; a decentralized approach to sanitation services is a must. Biogas/DEWATS is one alternative to septic tanks in Lesotho. Wastewater naturally produces biogas and purified water that still contains plant nutrients for reuse in the garden. Owners save money because they do not have to call (and pay) a truck to empty the septic tank every year or even in a very much shorter period; they can use the biogas for cooking, and they can use the water for irrigation, thus reducing the fresh water bill. The money saved within a reasonable time (some owners calculate a maximum of 3 years as period of internal return rate) can be used for further investments to develop the local economy.

The costs for a biogas digester and related wastewater posttreatment steps are divided into production costs, running costs, and capital costs:

- Production costs include all expenses necessary for the erection of the plant (e.g., land, excavation work, construction of the Biogas/DEWATS, piping, and gas utilization system). The construction costs comprise wages and material. They depend on size and dimensioning of the biogas unit, amount and prices of material, and the labor.
- Running costs occur in some cases more often and in some cases rarely; they could include feeding and operating of the plant; supervision, maintenance and repair of the plant; storage and disposal of the slurry; gas distribution and utilization, and administration. The running costs of a biogas plant with a professional management are just as important as the construction costs, for example, for operation, maintenance, expenses for painting, service, and repair.
- Capital costs consist of redemption and interest for the capital taken up to finance the construction costs. It has to be mentioned that many customers provide themselves with, e.g., building material to cut their costs; therefore, just a few have to borrow money. In calculating the depreciation, the

economic life span of plants can be taken as 15–20 years, provided maintenance and repair are carried out regularly. The money, which is saved by using “waste” as energy source and irrigation water, needs to be calculated for each specific case.

TED’s clients have various problems and therefore various reasons why they want to have a Biogas/DEWATS. That is why the “real” investment costs can be higher than the “real” outcome costs. But the problem, for instance a septic tank, which is always overflowing, is solved. Additionally, it is true that one saves a lot of money by having this technology. There is just the question if the client can furnish the start capital to invest in this technology.

Environmental Sustainability

The following analysis refers to international experiences:

- Wastewater and manure are naturally treated by bacteria, which upgrade wastewater and stabilize sewage sludge. The system improves the fertilizer quality of human and animal waste.
- It reduces the greenhouse gas emissions by using the produced biogas.
- Protected areas or the ecosystem are not affected because the construction is realized close to villages. As the system is mostly underground, the landscape is not damaged or negatively influenced.
- The treated water – still containing plant nutrients – should be (and is) reused for irrigation.
- Where biogas is an alternative to fossil-based fuels, it is, on a national level, considered to improve the balance of payments since less oil products have to be imported.
- On the individual level, system owners save valuable fresh water resources by using treated wastewater for irrigation; in addition, they do not need mineral fertilizer because the irrigation water still contains valuable plant nutrients.

Technical Sustainability

Low-tech biogas plants are related to low-volume efficiency; therefore, simple design and low-cost construction materials are required to compensate this disadvantage with larger digestion volumes, multiple

step treatment system, and even posttreatment steps – if sanitization requires. Therefore, creative solutions have to be developed by the designers to integrate these required volumes in the given space, often solved by underground constructions, cylinder designs or round shape design, which allows also construction material economy combined with optimal strength. Local service structure must be established for maintenance, spare parts, and repairing. In order to assure technical sustainability and continuous updating of technical staff, TED Lesotho applies the following approaches:

1. To be integrated into worldwide networks and close cooperation with technology and research partners like Bremen Overseas Research & Development Association (BORDA), University of Science & Technology Beijing–Centre for Sustainable Environmental Sanitation (USTB-CSES), and Water and Sanitation Association of Zambia (WASAZA).
2. To offer – in collaboration and consultation with cooperation partners – service packages to integrate the technology into an environmental sanitation concept. This includes, e.g., school sanitation, community-based sanitation, and sanitation systems for hospitals, hotels and tourism resorts, military camps, and for agricultural enterprises.
3. To include Research & Development into implementation in order to achieve safe upscaling of implementation; R&D includes the following topics (list not exhaustive): (a) sanitation & renewable energies; (b) sustainable environmental sanitation, and (c) agriculture & livestock. Regular monitoring of the system performance and external evaluation of the results by academic cooperation partner support these R&D activities. TED thus offers researcher opportunities to gain experience in reuse-oriented wastewater treatment systems under Lesotho-specific conditions.
4. To train system owners and operators and to offer after-sales services: Well-informed system owners and operators ask only in very critical situations for special maintenance activities to be provided by TED staff. Experience shows that owners, understanding that Biogas/DEWATS functions due to a well-maintained biology of microorganisms, are operating their wastewater treatment system throughout the

years without any problem, and without requiring additional maintenance support. During the first 12 months after construction, TED provides training and accompaniment to the owners and operators (in the case of community, school, or enterprise connected systems) in order to familiarize the responsible person with all relevant details to maintain a successful wastewater treatment process for biogas production and irrigation water reuse.

Lessons Learned

TED's experience and "success story" shows that there are acceptable, affordable, and environmentally safe sanitation technologies based on anaerobic digestion, already successfully installed in urban settlements in Lesotho. Given the fact that TED is implementing Biogas/DEWATS without any subsidies but fully paid by the customers, it is clear that a sanitation market is viable. Sanitizing wastewater on the compound, making it fit for irrigation, saving valuable drinking water, and encouraging home gardening especially in an HIV & AIDS suffering country clearly helps to improve the living conditions of the population. Turning organic waste (solid and liquid) into biogas for cooking is an important measure for climate protection, climate change mitigation, and resilience.

Challenges encountered and relevant for the way forward are craftsmanship's quality, expertise in Biogas/DEWATS construction, ownership, and how to cope with the increasing demand. TED's way of dealing with these challenges is and was always developed in a very pragmatic manner due to its characteristics as a nonprofit-making NGO in a country with an endless number of constraints and limitations. The following overview should be read as an outline for "lessons learned" on how to upscale implementation of "biogas for sanitation" purposes:

- **Craftsmanship's Quality:** TED engages in continuous quality control of its construction staff. In cooperation with international partners, quality parameters have been established, in-house training is carried out, and a quality management system related to Biogas/DEWATS construction is in place.
- **Expertise in Biogas/DEWATS construction:** Considering the limited labor market for specialized

technical professionals in Lesotho, TED encounters difficulties in identifying and hiring qualified civil engineers. International cooperation partners currently provide engineering expertise in Biogas & DEWATS construction, but contacts with national sector institutions are sustained and enforced to achieve knowledge transfer on a long term.

- Ownership: When a Biogas/DEWAT system has been sponsored by a third party and not – at least in a significant part – been financed by the system owner himself/herself, lack of responsibility and ownership often leads to system performance problems. This could also be observed in cases of community-based systems. TED therefore developed a user training principle that includes not only the technically responsible person but also the person who will benefit most from a well-functioning Biogas/DEWATS – like the cook in a school or orphanage.
- Increasing demand: Increasing demand could only be answered by an increasing number of Biogas/DEWATS constructions; therefore, TED applied for funds from a private donor foundation to train masons, who became part of the TED construction team after an intensive on-the-job training.

Future Directions

Nowadays the highest degree of market maturity of low-tech biogas technology can be found in the area of housing wastewater in decentralized wastewater treatment systems (biogas sanitation or DEWATS), organic sludge treatment, agro-industrial wastewater pretreatment, and treatment of livestock manure. The use of the biogas technology in housing (municipal) wastewater treatment is currently experiencing a rapid increase in Chinese and Indian suburban development. Household biogas plants in developing countries are today usually promoted on a large scale in connection with rural cooking energy supply and environmental issues, and are installed particularly where water pollution through liquid manure from land area unbalanced livestock activities – small, medium, and large – is most severe.

The increasing emission of greenhouse gases, increasing water pollution, declining soil fertility, unsatisfactory

waste management, and the promotion of sustainable renewable energy supply must be seen as parts of the driving factors for biogas technology as one of the important hardware components in a chain of measures to counteract the mentioned challenges.

Due to the fact that often trained constructors leave to search non-rural income in cities and processing industries, the development of prefabricated (composite or membrane) low-tech biogas plant elements will dominate the future constructions. Maintenance issues and responsibilities will be settled by rural plumbers as water and gas supply infrastructure accompanies rural housing development processes. Highly efficient end-energy use appliances for biogas, developed and produced from specialized industries, as already could be learned from China, are contributing to farmers' kitchen hygiene as well as social status upgrading of rural households. Centralized biogas plants will dominate the technology development in densely populated areas as waste-to-energy treatment plants. They could deliver cooking gas for surrounding households, provide electricity and heat for living areas, and cold for dairy farms milk cooling chains.

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Biogas Substrates from Municipalities and Industries

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Article Outline

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Glossary

Bioenergy Energy from Biomass [1].

Biogas Gas originating from fermentation [2].

Biogas substrate Biomass that can be used for fermentation processes and which mainly are wet energy crops or residues.

Biomass Material from biological origin excluding material embedded in geological formations and transformed to fossil [1].

Biomethane Upgraded biogas generated through the removal of carbon dioxide.

Biomass residues Biomass originating from side-streams from agricultural, forestry, and industrial operations [1].

Black liquor Liquor obtained from wood during the process of pulp production, the energy content is mainly originating from the content of lignin removed from the wood in the pulping process [1].

Chemical oxygen demand (COD) Amount of oxygen needed for the complete oxidation of the compounds included in the water [4].

Contamination Impurities resulting from exposure to or addition of a poisonous or polluting substance to a fuel [1].

Economic biomass potential Fraction of the technical potential that can be used economically in the context of the economic framework [4].

Energy crops Woody or herbaceous crops grown specifically for their fuel value [1].

Fruit biomass Biomass from the parts of a plant which holds seeds [1].

Fuel Energy carrier intended for energy conversion that can be solid, liquid, or gaseous [1].

Herbaceous biomass Biomass from plants that has no woody stem and which dies back at the end of the growing season [1].

Horticultural residues Biomass residues originating from production, harvesting, and processing in horticulture, including greenhouses [1].

Landscape management residues Residues of woody, herbaceous, and fruit biomass originating from landscape, park, and cemetery management [1].

Realizable biomass potential Expected use of biomass for energy purposes that mainly is part of the economic potential, but can as well be greater is, the option of using bioenergy is subsidized [4].

Segregated biomass Landscape management residues.

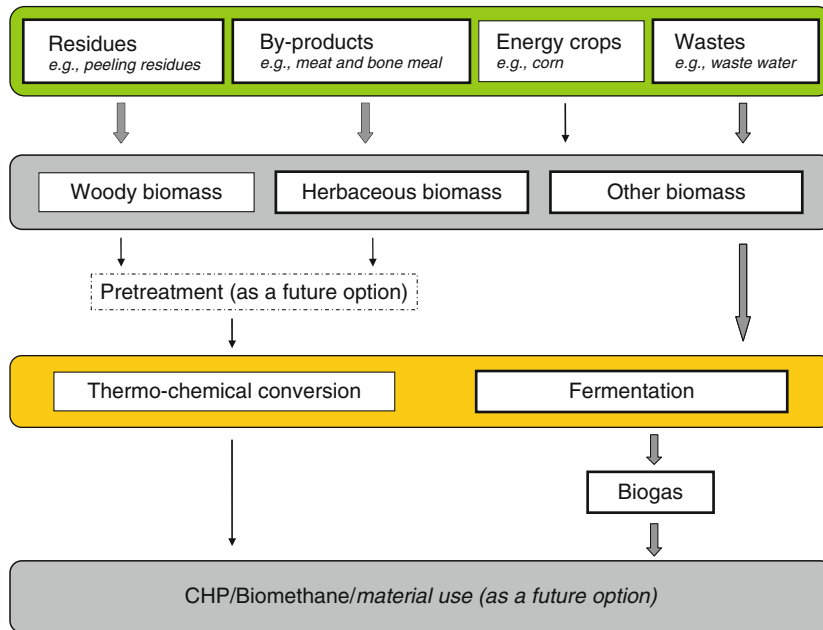
Sludge Sludge formed in the aeration basin during biological waste water treatment or biological treatment process and separated by sedimentation or flotation [1].

Technical biomass potential Part of the theoretical biomass potential which can be used for energy purposes given technical as well as structural and environmental restrictions, including priority for food and fodder production and material uses of biomass [4].

Theoretical biomass potential Theoretical limit of the available energy supply from biomass in a defined area [4].

Definition of the Subject

The production of biomethane can be done following two pathways as shown in Fig. 1. The established one is the anaerobic digestion of wet biomass and the adjacent upgrade of the resulting gas. The second one is based on the thermochemical treatment of solid (dry) biomass as wood. This article focuses on the anaerobic fermentation using residues from municipalities and industrial processes. This process in general includes the degradation of organic matter to acetic acid and other short-chain hydrocarbons as well as the conversion to CH₄, CO₂, and H₂O in an anaerobic milieu.



Biogas Substrates from Municipalities and Industries. Figure 1
Different categories of biomass and possible energetic uses

Suitable substrates have to show the following characteristics:

- Fermentative degradability
- Availability in aqueous milieu

The generation of biogas using anaerobic processes is possible for the conversion of wet organic biomass with little lignin content and organically polluted waste waters [4].

The term potential can be categorized as follows:

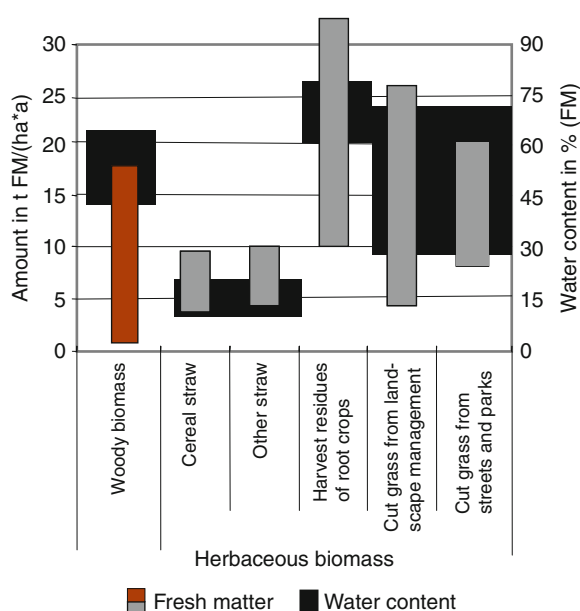
- The theoretical potential refers to a theoretical limit of the available energy supply from biomass meaning all phytomass and zoomass. Due to technical, economic, environmental, structural, and administrative restrictions, only a small part of the theoretical potential is available for energy uses.
- The technical potential describes the part of the theoretical potential that can be used given current technical possibilities. The calculation of the technical potential considers available utilization technologies and their efficiency as well as structural, environmental (such as nature conservation areas), and other nontechnical restrictions.

- The economic potential refers to the fraction of the technical potential that can be used economically in the context of the given economic framework. The economic potential is affected, for example, by the development of conventional energy systems and prices of energy sources.
- The realizable potential depicts the expected current use of bioenergy. Usually, it is lower than the economic potential, but can also be greater if, for example, the option of using bioenergy is subsidized in the framework of a market introduction programme [4].

The explanations of biomass potentials for the different categories of residues within this paper refer to the technical potential. Furthermore, the focus is put on biomass fractions which are currently available.

Introduction

Residues, by-products, and wastes are organic materials (biomass) which are generated next to the production of other goods and are suitable for an energy use. These biomass fractions could result from agriculture,



Biogas Substrates from Municipalities and Industries.

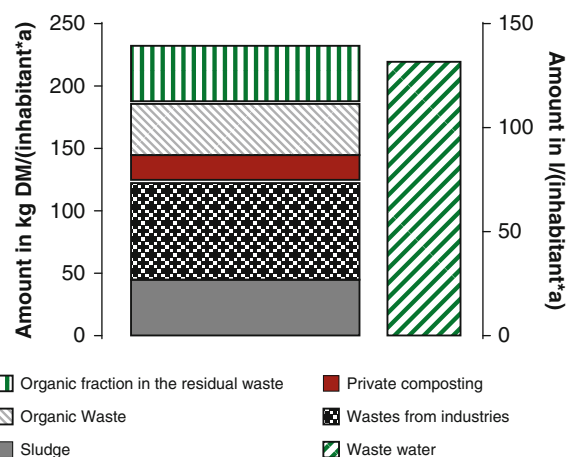
Figure 2

Bandwidth of area-specific amounts of selected residues, by-products, and wastes in Germany

forestry, as well as industry. Furthermore wastes from municipalities with high contents of organic matter are included [2]. This kind of biomass can arise generally during the whole provision chain from supply, production, and use up to the disposal of the organic material.

Residues generally arise depending on area or population, as well as production capacities. Therefore the generated amounts are very heterogeneous based on different factors as climate, type of cultivation, gross national product, and wastes. Especially the amount and composition of industrial wastes vary to a great extent since manufacturing processes have a huge influence regarding the residues and wastes.

Figure 2 shows area-specific amounts of some residues, by-products, and wastes typical for Germany to illustrate the diversity and partially considerable differences of such mass flows. Additionally, Fig. 3 shows examples of generated amounts of significant organic mass flows depending on the population which could be used energetically. According to that especially organic wastes, particularly from industrial processes, provide a substantial population-specific potential.



Biogas Substrates from Municipalities and Industries.

Figure 3

Average specific amount of selected organic residues, by-products, and wastes from households and industry, exemplarily for Germany (2003); the amount can differ regionally; the amounts of manure and organically polluted waste water are not included

Regarding this background, the intention of the following explanations is the presentation of different organic by-products, wastes, and residues from municipalities and industrial processes.

Biogas Substrates from Municipalities

Organic biomass resulting from municipalities can be herbaceous biomass from landscape management measures as well as waste and sludge from households. Some of these materials can be used for the production of biogas. Below these residues and wastes are characterized and their worldwide potential determined.

Landscape Management Residues

Segregated herbaceous biomass results from management measures in gardens, parks, cemeteries, and roads. They accumulate in varying amounts. The herbaceous biomass can be used as biogas substrate.

Herbaceous biomass can result from management measures beside roads. But some of the material stays next to the road because the collection is intensive in labor and costs and thus not realized. In Germany, for example, a collection rate of around 50% can be assumed. The collected material can be composted or

used for energy purposes, for example, as combustion fuel or biogas substrate. But considering the problems regarding the material collection, it does not seem very probable that herbaceous biomass from roadsides will be used for energy generation and especially as biogas substrate in a significant amount. Furthermore, in some countries, there are some limitations resulting from contaminant loads in the biomass.

Herbaceous biomass also arises in parks and cemeteries. The varying area-related amount of the biomass results from different management concepts (e.g., mowing once or more times per annum), and therefore clear and general statements about the available biomass are difficult to make. As an average value 20 t/ha of fresh biomass per annum can be assumed. Furthermore, the composition of this material is quite inhomogeneous and alternates in a huge range. In cemeteries, the amount of flowers, branches, etc., has to be added which cannot be quantified generally. The accumulated biomass often shows a high water content and isn't adapted to an energetic use. Also, some of the material stays on the area which helps closing the nutrition cycle. The rest of the biomass is collected and in most cases still composted although a use for energy purposes is possible. The fresh material can be used as biogas substrate or as solid fuel if it is dried in advance. But both applications are still an exception. Only in waste incineration plants a thermal utilization of the material is realized at the moment to certain extend.

Municipal Waste

Regarding the definition of the Intergovernmental Panel on Climate Change (IPPC) municipal waste includes all wastes collected in municipalities and/or other local authorities. Typically, it comprises household waste, commercial/institutional waste, as well as garden and park waste, and therefore organic compounds and used wood [1]. Below the potential and characteristics of the organic part of the municipal waste will be discussed since this can be used in biogas plants.

Because of its low dry mass content of around 40%, organic waste is particularly suitable as biogas substrate and not as a fuel for a thermochemical conversion [1]. Therefore anaerobic fermentation is used especially in Central Europe, but develops as well in other regions. But this is also a promising option for rural areas in

Asia [3]. Competing uses of the organic waste as material uses don't arise because the digested residue can be used as fertilizer following an aerobic treatment (composting) [4].

The amount of the municipal waste depends more or less directly on the population. The huge amounts of organic waste accumulate in countries with a huge population as China and the USA. In the USA, the generation rate of municipal solid waste is around 1.14 t/cap/year and therefore the highest rate worldwide (Fig. 4). In China, this generation rate is only around 0.27 t/cap/year. Approximately 40% of the waste materials are of organic origin. Also the state of the industrialization is an important factor. The more advanced the industrialization process the more municipal waste is produced.

At present, the organic waste is not separated from the rest of the municipal waste in most cases. This is a huge obstacle regarding the energetic use as a biogas substrate. A separation is common only in Central Europe, but here as well some impurities as plastics cannot be avoided [2].

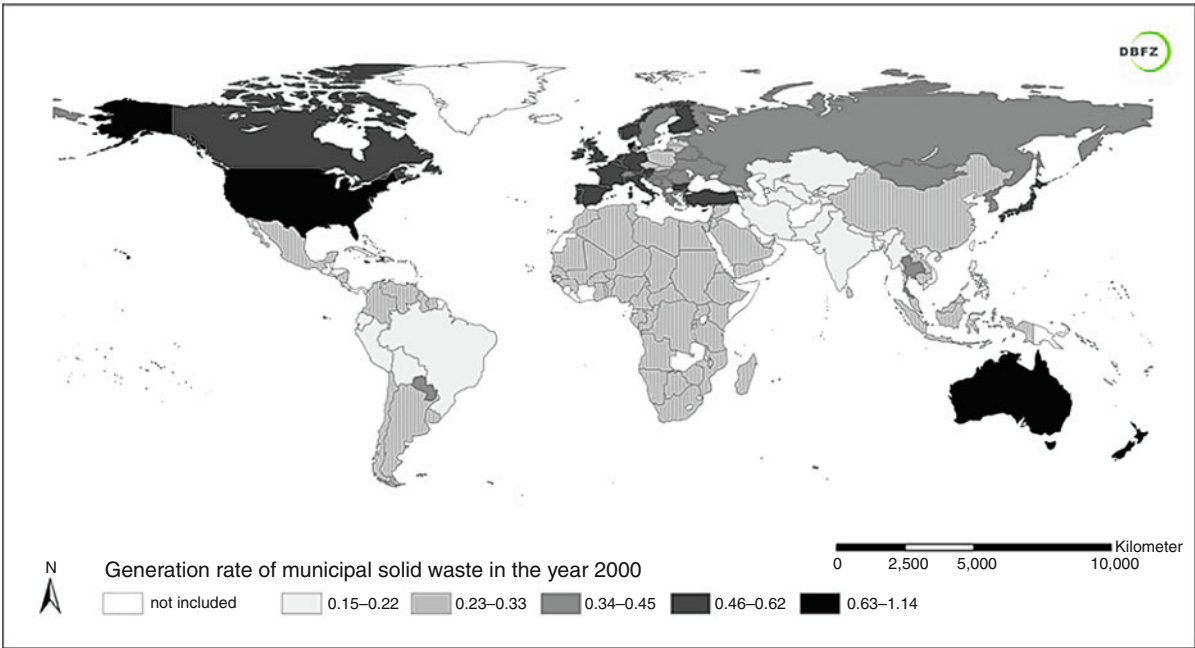
With regard to the access to the substrates, a general collection rate of 75% can be reached in the medium term if the efforts are intensified accordingly.

This leads to a technical potential of 1,160 PJ from organic waste in 134 countries which correspond to around 94% of the world population. The highest potential offers Asia with more than 500 PJ (Fig. 5).

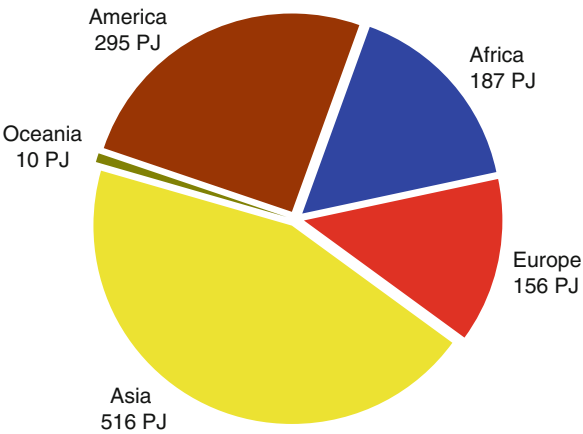
Sludge/Organically Polluted Waste Water from Municipalities

Sludge and organically polluted waste water result from domestic and industrial waste water treatment processes [1]. Aerobic and anaerobic processes can be used for the treatment of these waters. The aerobic treatment is much more common and has a long tradition. However, a huge disadvantage is the high amount of energy needed during the process as well as the great deal of sludge resulting of the treatment. Anaerobic processes on the other hand need more strongly defined conditions and are advantageous especially with a huge part of organic compounds.

Waste waters from municipalities result from households, municipal facilities (schools, hospitalities), and small companies (laundries, restaurants).



Biogas Substrates from Municipalities and Industries. Figure 4
Specific waste production rate in different regions and countries



Biogas Substrates from Municipalities and Industries. Figure 5
Technical potential of municipal waste in different regions in the world

Table 1 shows typical amounts of wastes in the waters exemplarily for Germany. Sewage from municipalities is characterized by variable amounts of pollutants. Roughly one half of these pollutants are of mineral origin (e.g., sand, ash) and organic compounds (e.g.,

excrements, food residues). The waste water is characterized by variations regarding the arising amounts, the composition and the degree of pollution during the seasons and the day. A minimum of the waste water amount is typical in the morning and in winter and a maximum at noon.

Municipal waste water treatment plants separate organic material using a preceding mechanical treatment. Thereafter the waste water is cleaned with aerobic microorganisms which results in a surplus sludge consisting of these microorganisms. Together with the organic sludge from the mechanical treatment, it is fermented in an anaerobic process within a digester. During this process, sewage gas develops which can be used for energy purposes. At first, not the generation of energy but the stabilization of the sludge has been the priority of this specific treatment. But until now, the digesters are also connected to a combined heat and power plant (CHP) to use the energy content of the sewage gas and to contribute to the energy supply of the waste water treatment plant. The quantity of sewage gas averages adds up to around 0.52 m³/kg organic dry substance in the sludge. The composition of the sewage gas is very similar to biogas. In the past, a huge part of

the sludge was used in agriculture and horticulture. Due to more strict limits for selected trace elements more and more sewage sludge is co-fired together with coal in coal fired power plants [2].

Biogas Substrates from Municipalities and Industries.

Table 1 Average pollution of municipal waste water exemplarily for Germany [2]

	Mineral compounds	Organic compounds	Sum
	in g/(inhabitant*day) or in g/m ³ (in parentheses)		
Sediments	20 (100)	30 (150)	50 (250)
Suspended compounds	5 (25)	10 (50)	15 (75)
Dissolved compounds	75 (375)	50 (250)	125 (625)
Sum	100 (500)	90 (450)	190 (950)

Biogas Substrates from Industries

Industrial wastes are those products of a production process that are not reused or recycled and arise next to the production of the primary product. Furthermore, by-products can accumulate during the production. Rather than being waste, these biomass can be reprocessed and used for various material and energy purposes. The residues which amount to significant quantities all over the world can be, for example, residues from the food production industry and from the pulp production or waste paper treatment. [Table 2](#) shows the most important categories of potential biogas substrates generated in the industrial production processes, including characteristic values [2].

The organic residues from industrial processes are often characterized by high water contents and huge loads of nutrients. Therefore a large part of the residues is used for animal feeding and is not (or only in restricted amounts) available for energy purposes. In the course of the industrial processes, a lot of waste water accumulates which could be used for energy generation through anaerobic fermentation [2].

Biogas Substrates from Municipalities and Industries. Table 2 Residues resulting from collected industry segments [2]

Industry segment	Substrate	Typical production specific amounts of waste	Typical organic dry matter content
Cereal manufacturing	Bran, husks, pastry residues	0.2–0.3 kg/kg cereals	85–97%
Manufacturing of fruits, vegetables, and potatoes	Peeling and cleaning residues	0.1–0.35 kg/kg feedstock	20–60%
Sugar production	Chips, molasses	0.7 kg/kg sugar	35–85%
Vegetable oil production	Press cake	1–3 kg/l vegetable oil	80–85%
Beer production	Draff, barm	0.25 kg/l beer	12–25%
Wine production	Marc	0.2–0.3 kg/l wine	30–55%
Alcohol production (distilleries)	Mash	1–3 kg/l ethanol	5–9%
Milk treatment	Whey, mixed with washing water	1–2 kg/l cow milk	5–7%
Meat processing/butchery	Rumen content, meat and bone meal, animal fat	15–60 kg/animal	8–98%
Pulp production	Black liquor	2–3 kg/kg pulp	35–50%
Waste paper treatment	Sludge	0.1–0.3 kg/kg waste paper	40–55%

The specific industrial residues listed in Table 2 will be outlined in the following. Additionally, organic wastes result as well, for example, from the processing of tea and coffee, the production of natural fiber and textiles, the manufacturing of leather, and some further industry sectors [2].

The following numbers given in the text below are valid mostly only for industrialized countries. Furthermore, they can vary significantly in particular cases.

Residues from Cereal Processing

Before cereals can be processed in the baking industry, they have to be ground in mills. There, residues as bran and hulks accumulate which amounts to around 20% of the delivered cereals. Ninety percent of the residues are bran which is used as fodder today. The husks that accumulate additionally during the process can be used as biogas substrate or combustion fuel but could also be composted. Additionally to these residues a certain amount of cereals can be used energetically because of an infection with mycotoxins caused by the weather. These infected cereals cannot be used for the food production any more. These organic residues have to be incinerated.

During the processing of the meal in the baking industry, pastry residues accumulate amounting to 10% of the produced pastries. These residues can be used in biogas plants. All residues from the cereal production show a huge amount of dry matter. Waste waters arise to a small degree regarding to washing and peeling processes [5]. The highest amounts of residues

from cereal production can be expected in Asia where most cereals are produced (Table 3).

Residues from the Manufacturing of Fruits, Vegetables, and Potatoes

This group of residues contains quite a lot of producers and products (e.g., fruit juice, vinegar, dry fruits). The fruits, vegetables, and potatoes are mostly of agricultural origin and are processed in bigger companies of the food industry. Different organic residues and wastes as peeling residues, washing waters of fruits, and pressed out fruits can accumulate during the treatment. Further possible residues are filtration residues, draff, and marc from the distillation of fermented fruits, potato peels, concentrates, returned goods, and more. Depending on the production process, different amounts of residues (10–30% of the fruits, vegetables, and potatoes) can arise. These materials can be fermented, composted, burned, or used in other ways as the production of alcohol, soups, pectin, aroma, and cosmetics. Furthermore, organic polluted waste waters can accumulate amounting to 1–3 m³/t of the product which could be used in the farm animal keeping [2].

Residues from fruit originate from the production from fruit juices and derived products. Due to an increasing popularity of these products, the amounts of the residues rise as well. The most important fruits are citrus fruits, apples, and grapes. Around 27 mn t of the citrus production are processed to juice, essential oils, and other products which leaves around 50% of the fresh fruit weight as a by-product. The world apple production comprises approximately 54.2 mn t of apples whereof China alone produces 25 mn t. Apples which are not suitable for consumption generate large amounts of residues which can be processed. In total, around 14 mn t of apples are processed for the production of juice, pulp, and jelly (Table 4). Apple pomace results from the fruit pressing and represents up to 30% of the fresh fruit. Grapes can be processed to wine, juice, jams, and raisins. In total, 58 mn t are produced annually especially in Italy (16%), France (12%), the USA (11%), and Spain (10%). Eighty percent of these fruits are used for wine making, and as a by-product from the production, grape pomace results in an estimated amount of 13% of the original fruit.

Biogas Substrates from Municipalities and Industries.

Table 3 Total cereal production in different regions worldwide [6]

	Total cereal production (t)
Asia	1,188,100,000
Africa	151,370,000
Oceania	34,560,000
Europe	504,365,000
America	646,710,000

Biogas Substrates from Municipalities and Industries.**Table 4** Amounts of processed citrus, apples, and grapes worldwide per annum and resulting by-products, respectively, residues

	Processed amount (mn t/a)	By-products/residues (%)	By-products/residues (mn t/a)
Citrus	27	50	13.5
Apples	14	30	4.2
Grapes	46.4 wine	13	6

Residues from Sugar Production

Sugar can be produced from sugar-beet or from sugarcane. The production of sugar based on sugar-beet generates crystal sugar amounting to around 17% of the original weight of the beet. The residues are wastes from sugar-beet (around 1.5 kg/kg of sugar), pulp, and molasses (0.24 kg/kg sugar). Currently, these mass streams are used for the production of syrup and yeast and as fodder. Additionally, huge amounts of organically polluted waste waters result, for example, from the washing of the sugar-beet and the chemical extraction of crude sugar. These waters however are recycled and used in the process water cycle.

Residues from Vegetable Oil Production

Additionally huge amounts of residues, wastes, and by-products result from the production of vegetable oils. The production of 1 l rapeseed oil, for example, leads to 1.4 kg rapeseed cake or rapeseed meal. These by-products are often used as fodder for animal breeding. If the rising demand for oil as fuel leads to higher amounts of residues, the additional rapeseed cakes and rapeseed meals could be used for energy purposes. Especially the use as combustion fuel seems promising. Furthermore, the glycerine from the process of transesterification could be an interesting residue.

Residues from Beer Production

The manufacture of beer involves the generation of some typical by-products and residues which are

Biogas Substrates from Municipalities and Industries.**Table 5** Residues from the production of 100 l of beer

	Residue per 100 l of produced beer
Spent grains	2,000 g
Spent hop	100–300 g
Surplus yeast	?

spent grains, hops, and surplus yeast. These result from the processing of the raw materials and are available in huge amounts because the use is still limited. Therefore the residues represent large potentials for various uses which would also be a solution to environmental problems which arise with the disposal and land filling of the material.

The by-products from the beer production can accumulate as a residue from the malting at the end of the process and comprise the husks of the malt which are rich of cellulose. Furthermore, it consists of nitrogen and vegetable fats and is therefore used as fodder, for example, in the dairy farming. Other possible uses are in biotechnological processes as fermentation, as substrate for the cultivation of microorganisms, or as raw material for the extraction of proteins, sugars, and acids [7].

Additionally, 2.5–6 l waste water arises from the production of 1 l beer which can be treated in biogas plants together with the other residues [2]. Furthermore, 200 t of spent grains (70–80% water content) are generated with the production of 10 mn l of beer. They are basically composed by barley grain husks. The material is rich in cellulose, hemicellulose, and lignin and has high protein content. The hop is used for the brewing and is rich in components which supply the bitter and aroma components to the beer. However, 85% of the raw material ends up as residues [7]. For the production of 100 l of beer, 100–300 g of hop is needed, and therefore 85–255 g are left as residue (Table 5). The third residue of the brewing process is the surplus yeast. However, it is not easy to state how much of the yeast is left for other uses because it can be used for the next brewing process.

In 2008, the global beer consumption reached 146.2 billion litres which would cause around 365.5–877.2 billion liters of waste waters [6].

Residues from Wine Production

The production of wine is a very important industry in many countries all over the world and generates huge amounts of organic residues such as sugars and cellulose. One of the residues is distilled grape marc which is a complex lignocellulosic material [7]. It is produced after pressing the grapes in white wine processing or after the fermentation and maceration in the red wine production. The production of 100 l of wine generates 25 kg of marc and 200–300 l of waste waters as residues. These are used especially in distilleries or in agriculture as fertilizer or animal feed. As an alternative the fermentation in biogas plants is possible as well [2].

In 2008, the wine production reached around 27,270 million liters [6]. Therefore the amount of residues generated worldwide was about 6,818 million kilogram of marc and 54,540–82,810 million liters of waste waters.

Residues in Distilleries

The fermentative conversion of sugar (e.g., from fruits) and starch (e.g., from cereals) to ethyl alcohol is made in distilleries. This processes of fermentation and distillation generates residues (draff, stillage) which can be used energetically by an anaerobic fermentation. The production of 1 l ethanol from cereals produces around 10–14 l of wet stillage (2–8% of dry substance) which can be concentrated to 0.75 kg of dried distillers grains with soluble (DDGS). The draff can be used as fertilizer on agricultural areas or as animal feed. Thus, distilleries are predominantly in peripheral areas and a use could only be reasonable if the generated energy can be used locally [2].

Residues from Milk Production

Whey is the characteristic by-product of the processing of milk to cheese, curd, and cream cheese. It can be distinguished between sweet whey and acid whey which is generated using lactic acid producing bacteria. Furthermore, waste water accumulates amounting to about 2 m³ per liter milk. With a total milk production of 690 mn l in 2008 [6], this would generate about 1,380 mn l of waste water. Generally these waters are mixed with other solid and fluid residues and reprocessed to whey

powder and drinks or used as fodder for pigs, etc. In some cases, the residues can be fermented in biogas plants [2].

Residues from Meat Processing

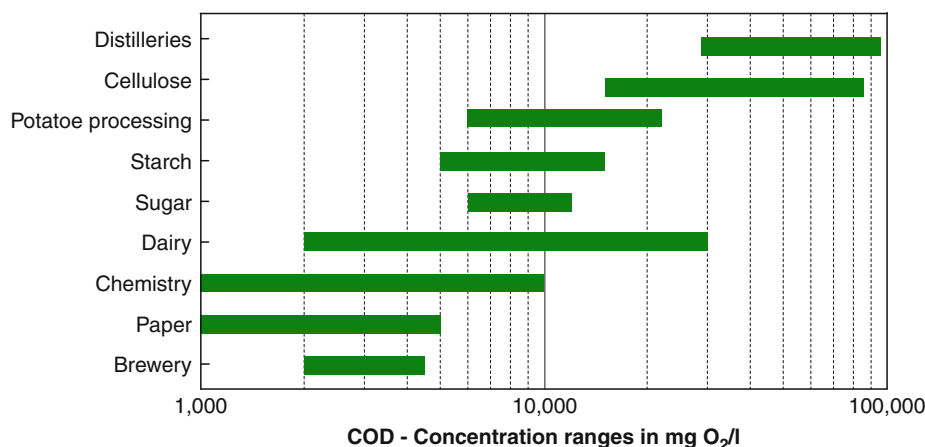
Every year, around 50,000 head of cattle, 500,000 pigs, and 28,000 sheep, goats, and horses are slaughtered per one million inhabitants, for example, in Germany. The residues from the slaughtering amount to 30 kg per inhabitant in a year. These can be used for material as well as for energy purposes. Especially since the emergence of BSE meat and bone meals are applied in the chemical industry and for the production of fertilizer. Furthermore, few plants for the generation of methyl ester from animal fats to be used as fuel exist, for example, in Germany. Prospectively, the recycling of phosphate from meat and bone meal could gain in importance [2]. Nevertheless, there is indeed a potential of such residues to be used as a feed for biogas plants.

Residues from Pulp and Paper Production

In the pulp and paper industry, two processes have to be distinguished: the generation of cellulosic pulp and the production of paper and cardboard. The production of cellulose leads to the generation of black liquor. It contains the lignin part of the wood which cannot be utilized for the paper production. Black liquor is already used in most paper plants as a fuel to meet the internal energy demand. Another residue of the pulp and paper production is industrial sludge contaminated with fiber which could account up to 30% of the raw material. These sludge can be dried and combusted as a solid fuel. They can as well be used for material purposes such as amelioration in the agriculture and for the production of bricks. Furthermore, huge amounts of waste waters accumulate during the paper production process – around 10 m³/t paper produced [2]. This waste water can be treated under anaerobic conditions.

Sludge/Organically Polluted Waste Water from Industries

Organically polluted waste waters from industries are characterized by huge variations in the available



Biogas Substrates from Municipalities and Industries. Figure 6

COD – Concentration ranges of waste water from different industrial sectors [4]

amount throughout the course of a day or a year. Variations can as well be observed regarding the degree of contamination which varies especially in sugar refineries, vegetable processing, and distilleries and depending on technical aspects. Internal water circulation, for example, leads to considerable reductions of waste water amounts. On average, 2–3 m³ of industrial waste water accumulate per inhabitant and year in Germany. Typical contaminations are around 1,000 and 100,000 g COD/l (COD describes the amount of oxygen needed to oxidize all ingredients completely; Fig. 6). Industrial sludge account to up to 10 kg_{DM} per inhabitant and year, for example, in Germany, and is used for energy purposes almost completely [2].

Future Directions

Residues from industrial processes and municipalities are diverse and offer various possibilities for material and energy. Furthermore, residues offer huge potentials for the production of biogas, although it is difficult to quantify the potentials of all residues and by-products worldwide since statistical data are not available in many cases. Additionally, a part of the biomass is already in use. They can be used for material purposes or for feed and fodder such as rapeseed cakes. Other materials are already in use for energy purposes such as black liquor which

covers parts of the internal energy demand of paper production plants.

The future trends regarding the amount and availability of municipal and industrial residues and by-products for the biogas production depend on the development of the population, the progress of the industrialization process, and development of the specific industries. Furthermore, competitive uses have to be considered.

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Biomarkers and Metabolomics, Evidence of Stress

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Article Outline

Glossary
Definition of the Subject
Introduction
Applications of Metabolomics
Future Directions
Acknowledgments
Bibliography

Glossary

Stress Any change(s) in physiology and biochemical process that causes deviation from a normal state of an organism and requires an adjustment to return to the normal state.

Stressor An agent, condition, or other stimulus that causes stress.

Biomarker A biological chemical or macromolecule used as an indicator of a biological state that is often reflected by changes in its concentration.

Toxicity Degree of poisoning or damage caused by a substance to an exposed organism.

Metabolome The whole set of metabolites, forming an extensive network of metabolic reactions, in a biological system (e.g., an organism, organ, or cell).

Metabolomics Comprehensive study of a metabolome or a set of metabolites in which one metabolite from a specific pathway affects one or more biochemical reactions, or a comprehensive and quantitative analysis of all metabolites.

Omics Comprehensive study of a biological system. Omics fields include genomics, proteomics, metabolomics, and transcriptomics.

Definition of the Subject

To evaluate the biological effect(s) of a stress, it is necessary to identify and characterize the stressor (s). In general, stressors can be classified as toxicants, pathogens, and physical stimulants. Although the reactions and the degree of response may vary, stressors frequently induce extensive metabolic changes in a living organism. Comparative research on a large set of metabolites at different stress states can provide detailed insights into specific biochemical reactions and metabolic networks. Such information can be used for diagnosis of a disease or toxic effect, development of therapeutic remedies to relieve the stress or its detrimental effect, etc.

The rapid accumulation of genomic and proteomic information of various organisms and rapid advancement in analytical capability make new disciplines of omics possible. In comparison with conventional approaches that usually focus on specific biochemical pathways, a major interest of omics is to gain system-wide information about the target organism and biochemical events. The main goal of metabolomics is qualitative and quantitative differentiation of an entire set of metabolites and the biological networks in the target organism [1, 2]. Metabolite profiles, fingerprints, and related concepts have been applied in various biochemical and toxicological studies since the 1980s [3, 4]. Metabolomics is an emerging discipline and has been shown to be a powerful tool for biomarker discovery and stress research. A related term, metabonomics has also been widely used in the

literature. In this chapter, both metabolomics and metabonomics are regarded as having the same meaning. This chapter discusses the metabolomics of animals, plants, and microorganisms relevant to environmental toxicology.

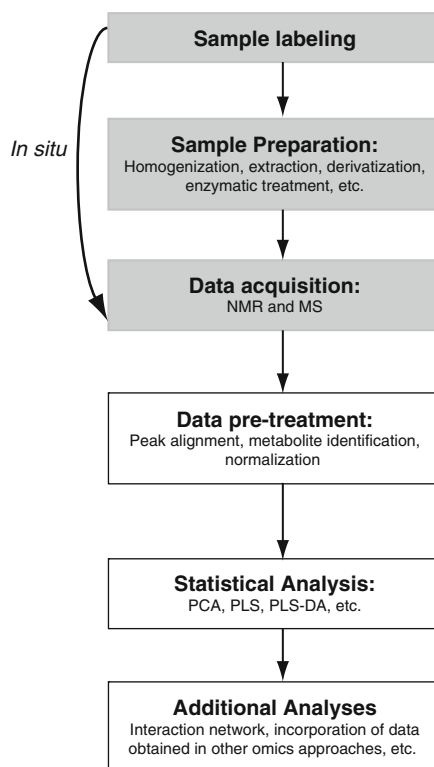
Introduction

Biomarkers provide direct evidence of stress or potential stress. There are different types of biomarkers. Some biomarkers indicate different stages of disease: early threat (i.e., risk indicator or predictive biomarkers), existence (i.e., diagnostic biomarker), and disease development (i.e., prognostic biomarker). Some biomarkers give an indication of chemical toxicity, while others indicate physical stresses. It is widely known that cholesterol values are a biomarker indicating coronary and vascular disease risks. Molecular biomarkers need to be naturally stable for chemical analysis, to be reliably quantified, and to be effective for diagnosis, prognosis, and risk assessment. In environmental toxicology, biomarkers play a major role in environmental risk assessment, exposure, and management. Biomarker-based biological monitoring aids in early risk diagnosis, risk prevention and minimization, action target identification, toxic response, bioremediation, etc. The analytical method for a biomarker must be accurate, simple, reproducible, and cost-effective. Many genomics, metabolomics, and proteomics techniques are available for biomarker discovery. It is noteworthy that discovery of a biomarker typically requires a large amount of research effort. Biomarkers can be difficult to validate and may require different levels of validation.

Metabolomics has been largely employed to analyze all metabolites (i.e., global analysis) in a biological sample. Metabolomics experiments typically involve sampling, sample preparation, extraction, fractionation, detection, measurement, and data mining and management. Although metabolomics concerns the entirety of metabolites as analytical targets, it is practically impossible to cover all with a single analytical method. A large portion of metabolites are water-soluble, whereas steroids and respiratory quinones, for example, are practically water insoluble. It is well recognized that metabolomic responses are more rapid than other omics targets upon a stimulus. Hence,

cautious and rapid handling of samples is very important to preserve the integrity of the metabolome. Common sample preparation protocols include proper labeling and storage of biological specimens, homogenization, extraction, cleanup, and concentration (Fig. 1). Additional procedures are often used to enhance the data quality and instrument performance, including enzymatic treatment to remove proteins and excess metabolites. In a metabolomics study targeting a specific set of metabolites, specialized enrichment techniques are often utilized [5, 6].

Instrumental analyses are an integral step in metabolomics research. Metabolomics methodologies can be divided into chemical separations and measurements. Instrumentation commonly used in metabolomics includes nuclear magnetic resonance



Biomarkers and Metabolomics, Evidence of Stress.

Figure 1

A common metabolomics workflow. PCA, principal component analysis; PLS, partial least squares; DA, discriminant analysis

spectroscopy (NMR) and mass spectrometry (MS). MS is widely used in metabolomics because it can provide rapid and sensitive qualitative and quantitative analyses of metabolites [7, 8]. High selectivity and sensitivity can be achieved by using tandem mass spectrometer systems where a mass spectrometer is hyphenated with another mass spectrometer and/or coupled with a separation technique. Some mass spectrometers such as Fourier Transformation cyclotron resonance MS (FT-ICR MS) have enough resolution power, eliminating chromatographic or electrophoretic separation requirements [9–11]. NMR has been applied in metabolomics since the 1980s [4]. Its strengths include rapid data acquisition with minimal sample preparation time, high reproducibility, and rich structural information. These factors make NMR among the most popular tools for high throughput applications. Disadvantages in comparison with gas chromatography-MS (GC-MS) include low sensitivity and less comprehensive spectral libraries. Data from instrumental analysis require comprehensive interpretation, often accompanied by pretreatment of data (e.g., spectral deconvolution, peak alignment, and structural identification of specific metabolites).

A single metabolomics experiment can generate huge amounts of data leading to a comprehensive understanding of metabolic networks, whereas conventional approaches deal with a limited number of biochemical reactions. Complementary information from proteomics and genomics is often incorporated into a metabolomics data set to further interpretation of the biological events. Sophisticated statistical procedures are often necessary to uncover data of biological significance. Several data reduction methods, including principal component analysis (PCA), discriminant analysis (DA), partial least squares (PLS), and other newly introduced methods (e.g., Support Vector Machine and Neural Network) are used [12–15].

Integrated omics approaches are increasingly being used to verify and visualize metabolic differentiations. For example, Okuda et al. [16] reported the potential utility of the KEGG (Kyoto Encyclopedia of Genes and Genomes) atlas for global analysis of metabolic pathways and metabolomics. Many excellent reviews of metabolomics are available [17–22].

Applications of Metabolomics

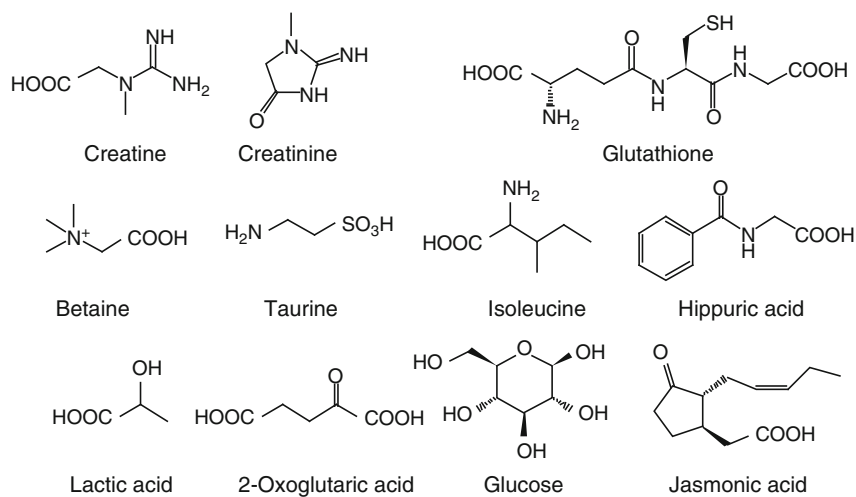
Metabolomics in Animal Sciences

Metabolomics is considered to be the most promising omics tool for system-wide evaluation of stressors because primary metabolites are well conserved throughout the phylogenetic kingdoms [23, 24]. Chemical, physical, and biological stimuli have been studied. Much of the current research deals with mammals challenged by diseases, toxicants, and pathogens. Applications in this field are centered on the discovery of biomarkers for specific stressors, as exemplified in Table 1. Furthermore, metabolomics can provide insights into mechanisms of stress response, which can assist in the development of proper treatment methods [25, 26].

Mammalian metabolomes are more complex than those of plants and microorganisms. The concentrations of different metabolites in the same sample vary dramatically. In addition, both the concentrations and chemical identities of metabolites vary largely among different organs, sexes, ages, physiological stages, and numerous other factors. One of the most noticeable recent advancements was the construction of a metabolite database [27]. The human metabolome database (HMDB) is a comprehensive data resource of metabolites found in the human body (<http://www.hmdb.ca>). Many toxicological studies via metabolomics are approached with metabolic fingerprinting and pattern recognition where knowing the exact identities of metabolites is not a prerequisite. Such applications of metabolomics have been used in clinical diagnostics. Biofluids such as blood and urine are commonly used samples. Figure 2 shows several common marker metabolites regardless of the stressor types (i.e., non-stress-specific biomarkers) [28–30]. In environmental toxicology, this type of biomarker can be used for the first tier of monitoring. The use of organic acids and creatine as biomarkers is often criticized due to their lack of stress specificity. It is noteworthy that the data from metabolomics should be interpreted on the basis of pattern changes rather than simple concentration changes of a few metabolites. The simple fingerprints along with structural identification can give comprehensive and detailed information of cellular status. Metabolomic profiles and structural analyses, for

Biomarkers and Metabolomics, Evidence of Stress. Table 1 Examples of metabolomics studies of stressed animals

Type of study	Animal	Stressor	Description	Reference
Biomarker discovery	Rat	Drug (acetaminophen)	Depletion of antioxidants as marker	[37]
	Rat	Heavy metal (As, Hg)	Accumulation of creatine, lactate, and decrease of some amino acids	[46, 47]
	Human	Food (chocolate)	Decrease of stressor hormone (cortisol) by chocolate consumption	[55]
	Rat	Physical stress (shaking)	Accumulation of glucose, lipid and repression of acetate, amino acid	[56]
	Various	Environmental stress	Review of stress-metabolomics of non-model organism in ecosystem	[17]
Mode of action	Rat	Cancer and drug	Mode of action of anticancer drug	[33]
	Rat	Triazole fungicide	Unexpected toxicity of triazole fungicides	[43, 44]
Database	Human	Nontargeted	Identification of metabolites in the metabolome of healthy adults	[27]
	Human	Miscellaneous	Construction of metabolite database (http://www.hmdb.ca)	[115]

**Biomarkers and Metabolomics, Evidence of Stress. Figure 2**

Structures of selected biomarkers in stressed animals, plants, or microorganisms

example, delineated a potential role for sarcosine in prostate cancer progression [31].

In drug discovery, many steps of evaluation are required, including screening for intended bioactivity (potency), adverse effects (toxicity), dose–

response (efficacy), and metabolism (detoxification). Metabolic modulation of xenobiotics (drugs and pesticides) can trigger complicated problems because the extensive structural modification of xenobiotics through metabolism can alter the

potency or toxicological profiles of the parent compounds. Holistic approaches, like metabolomics, may be a useful solution for drug discovery [32]. Metabolomic investigation of mode of action has been used to identify the exact targets and metabolic pathways of preclinical drugs. Watson et al. [33] identified the mode of action of an anticancer drug through global metabolic profiling. The mode of action of complex molecules (e.g., peptides and proteins) has been assessed with metabolomics. Angiotensin II (a well-known hormone) induces mitochondrial dysfunction. Mervaala et al. [34] used metabolomic methods to study the influence of angiotensin II on the metabolic profile and determine the mode of action of angiotensin II. They found that distinct patterns of cardiac substrate use in angiotensin II-induced cardiac hypertrophy are associated with mitochondrial dysfunction. In addition to natural primary metabolites, drug metabolites are profiled to obtain comprehensive data. The recent studies with naphthoquinone derivatives revealed that the toxicity of these chemicals is due to redox impairment, which causes strong oxidative stress [35]. It was found that oxidative stresses in response to acetaminophen in rats include depletion of antioxidants (e.g., ferulic acid), trigonelline, S-adenosyl-L-methionine, and energy-related metabolites [36, 37].

Pesticides are the cornerstones of pest management, food security, and public health. There are, however, public concerns about potential adverse effects of pesticides. Metabolomic evaluations of pesticide toxicity are much fewer than those of human drugs and diseases [38]. Similarly, a limited number of publications are available concerning metabolomics with organic pollutants. However, related research has gained some attention from scientific communities and regulatory organizations. Earlier studies of *in vivo* pesticide evaluation have indicated the complexity of the issue, particularly in higher animals. A specific pesticide can yield many metabolites with different toxicities [39–41]. In general, recently registered pesticides have much improved performance, including higher target selectivity, shorter half-lives, and fewer side effects (e.g., toxicity to nontarget organisms). In spite of these improvements, side effects are inevitable. Acetylcholine esterase is the target enzyme of organophosphorus insecticides (OPs). Some OPs are potent inhibitors of

cytochrome P450 (CYP), a key enzyme of xenobiotic detoxification [42]. Azole fungicides target the fungal sterol 14[α]-demethylase used in ergosterol biosynthesis, but some of them can also inhibit mammalian sterol 14[α]-demethylase. Ekman et al. [43] analyzed metabolomic differences between normal and triazole fungicide-treated rats. The differential accumulation and depletion of some marker metabolites (creatine, choline, some osmolytes, and branched amino acids) in a dose-dependent manner were observed. Distinguishable metabolomic patterns indicated chemical-specific stresses of these fungicides [43, 44].

Mammalian metabolomics in response to heavy metals are frequently reported. Several heavy metals such as arsenic, cadmium, and mercury are commonly known environmental contaminants, especially in mining areas. Mally et al. [45] reported that 4-hydroxy-2(E)-nonenal is a potential biomarker of toxic mineral exposure, and its accumulation possibly indicates heavy metal-induced renal failure. Metabolomic analyses in the sera of cinnabar (mercury sulfide)-treated rats showed elevated concentrations of ketone bodies (3-D-hydroxybutyrate and acetoacetate), branched amino acids, choline, and creatine and decreased concentrations of glucose, lipids, and lipoproteins [46]. Similar metabolic profiles were also found in rats in response to realgar (arsenic sulfide) [47]. Accumulation of creatine, betaine, and some nitrogen-containing metabolites was the common, characteristic response to arsenic and mercury. The levels of glutathione and *N*-acyl amino acids, however, varied depending upon heavy metals and tissues [46, 47]. Toxicities of nano-materials are an emerging issue. Nano copper particles induced extensive changes of rat metabolomes [48]. An increase in triglycerides in the serum, liver, and kidney tissues could serve as a potentially sensitive biomarker for nano copper-induced lipidosis.

Target analytes in most metabolomics are naturally produced metabolites. However, recent studies of drug metabolism in conjunction with profiling natural metabolites suggested and confirmed novel toxicity biomarkers and toxicity mechanisms [49–52]. These studies produced extensive metabolic profiles of specific chemical stressors (e.g., drugs, pesticides, or environmental contaminants). Because the potency or toxicity of metabolites may differ from the parent

chemicals, comprehensive profiling of metabolites can offer valuable information to evaluate chemical toxicity. Chen et al. [51] profiled both natural and drug metabolites and identified conjugates of acetaminophen metabolites as promising biomarkers of acetaminophen-induced toxicity. In addition, the oxidative stress elicited by CYP2E1-mediated acetaminophen metabolism might significantly contribute to its toxicity.

Recent studies have indicated several interesting aspects of nutritional metabolomics. Synergistic effects of co-application of anticancer drugs and methionine deprivation are well known for treatment of some cancers. However, the exact mechanism was not well understood. Guenin et al. [53] found that methionine deprivation affects several metabolite pools, including phospholipid and S-adenosyl-methionine. Changes of these metabolites are accompanied with abnormal expression of some proteins and other key metabolites involved in tumor proliferation. Colon cancer is associated with diet, including higher intake of dietary sugar. Hansen et al. [54] applied metabolomics to investigate the relationships between the incidence of colon cancer and sucrose, glucose, and fructose. These sugars increased mutation rates in the colon and bulky adduct levels in the colon and liver to a similar extent. The metabolomics studies indicated disturbed amino acid metabolism and a decrease in plasma and urinary acetate to be a common feature for all dietary sugars and confirmed triglyceridemic effects of fructose. Accumulation of DNA-adducts was usually accompanied with a decrease of antioxidants, especially methionine. Increased colon cancer with associated changes of metabolic profiles indicated that a high sugar diet may affect the biochemical environment and may increase the probability of cancer development. In comparison with other stress-related metabolomic research, effects of food are often difficult to study, since food is a very complex mixture of chemicals. Routes of absorption, distribution, metabolism, and excretion (ADME) of specific constituents in the tested food can influence metabolic responses. A recent study on human consumption of chocolate has illustrated interesting metabolomic effects and a strong correlation with psychological activity [55]. Decreased excretion (or levels) of cortisol (stress hormone) was the most apparent effect of chocolate in

reducing anxiety. This exemplifies the power of metabolomics to evaluate the effect of complex mixtures.

Animals are frequently exposed to physical stress (temperature, wound, etc.). Teague et al. [56] studied metabolomic responses of rats under physical stresses—namely, shaking the cage occasionally. They found several different marker metabolites, depending upon the shaking duration. As acute response, the accumulation of glucose and ketone bodies was accompanied with the repression of acetate and branched amino acids. Prolonged shaking induced additional metabolomic changes (e.g., increase of choline). A recent study with rats indicated that extensive metabolomic changes can occur during restraint stress [57]. Notable responses included differential levels of metabolites in glycolysis, the tricarboxylic acid (TCA) cycle, fatty acid oxidation, and urea cycles.

Environmental metabolomics, particularly targeting non-model animals, is more difficult because the needed information such as gene sequences and protein databases is limited, and the organisms are usually exposed to multiple stressors [17]. The recent social interests in environmental issues have accelerated such research needs. Metabolomes of various organisms were recently assessed, and fish were the most common model organisms. These species include Chinook salmon (*Onchorhynchus tshawytscha*), flatfish (*Limanda limanda*), fathead minnow (*Pimephales promelas*), and Japanese medaka (*Oryzias latipes*) [43, 58–62]. Although multiple stressors are common in the environment, metabolomic studies with these animals often focus on a specific stimulus (disease or chemical stress). Ekman et al. [58] reported that metabolomic responses to the fungicide vinclozolin in fathead minnows included changes in the concentrations of several metabolites including creatine and betaine. Viant et al. [61] reported that several metabolites, most notably of energy-related intermediates (e.g., ATP), amino acids, and creatine, accumulated in Chinook salmon exposed to the pesticides dinoseb, diazinon, and esfenvalerate. Japanese medaka also gave a similar response to dinoseb [62]. In general, hydrophilic metabolites are more common metabolomics target molecules. Steroidal lipids were also proven to be good marker metabolites in rainbow trout (*Oncorhynchus mykiss*) in response to environmental estrogens [59].

Recent metabolomics studies revealed the effects of pesticides on several invertebrate species such as earthworms (*Eisenia* spp. and *Lumbricus rubellus*) [63–68]. In a multi-platform analysis of earthworm metabolomes, McKelvie et al. [68] found that DDT and endosulfan affected the levels of sugars and amino acids. The comparative analyses suggested the ratio of alanine to glycine as a potential biomarker of pesticide exposure. Rochfort et al. [69] observed a clear indication of different metabolomic patterns in earthworms being relevant to soil health.

Mollusks such as abalones and mussels are usually considered to be relevant marker species of chemical stress in the marine environment. Tuffnail et al. [70] investigated metabolomic responses of blue mussels (*Mytilus edulis*) under various physical and chemical stressors. In this case, alanine and some osmolytes were the important factors to discriminate different stress types. Research with red abalone (*Haliotis rufescens*) also indicated several osmolytes, amino acids, and storage carbohydrates (e.g., glycogen) to be the common indicators of environmental stresses [71]. Metabolomics studies with either freshwater or marine-dwelling crustaceans are quite limited. Recent examples with *Daphnia* and *Diporeia* concerned the metabolomic evaluation of atrazine and heavy metals [11, 72]. Several amino acids and amines were characterized as useful biomarkers through the analysis of metabolomes. However, detailed connections between this information and other biochemical observations are still missing.

Birds are important parts of ecosystems and food resources. However, metabolomic research has been very limited in this subject. Approximately 300 research articles have been published in other omics areas for chickens, but only one metabolomic publication was found as of April, 2010. Huber et al. [73] studied the effects of organically and conventionally produced feeds on a chicken model. Small but noticeable differences of metabolic profiles were observed, which may be correlated with animal productivity. Research is needed to fill in the knowledge gaps of metabolomic responses to stressors in birds.

Metabolomic research has also been very limited in insects, which are important parts of ecosystems. Recent studies with *Drosophila melanogaster* indicated that several metabolites (e.g., glutamate and choline)

give differential responses against hypoxia and heat [74, 75]. Future metabolomics studies with insects are of great significance, particularly for ecosystems, agriculture, and food security.

Applications in Plant Sciences

Plants are fundamental to our life. Much research has been published on practically every aspect of plants. Most applications of metabolomics in plant sciences are phenotyping or simple mapping of metabolites. Many publications of plant metabolomics under various types of stresses have been published [76–79] although fewer than those concerning animals. Table 2 shows common physical, chemical, and biological stressors.

Temporal dynamics of metabolomes in heat and cold-stressed *Arabidopsis thaliana* have been monitored [80]. In general, cold shock influences metabolism far more profoundly than heat shock. However, a large portion of heat- and cold-shock responses overlaps. Those include accumulation of amino acids derived from pyruvate and oxaloacetate, polyamine precursors, and compatible solutes [80]. Rudell et al. [81] studied metabolomic changes of apples in response to cold and suggested that a wide array of metabolomes were changed under the specified conditions. Studies indicated that some antioxidants or plant growth regulators may alleviate the damage of cold stress. Although there were several unique responses, depending on the nature of stressors, physical stimuli usually induced accumulation of oxylipins [82]. Several jasmonate derivatives were identified as useful biomarkers of wound-induced response in *A. thaliana* [83] (Fig. 2).

Heavy metals are common stressors to plants. They are commonly used as toxicant models in metabolomics and other omics research. Plants that are highly tolerable to heavy metals usually produce a large amount of small peptides, called phytochelatins. Metabolic profiling of cadmium-treated *A. thaliana* has shown an accumulation of several phytochelatins [84]. Phytochelatins are oligomers of glutathione containing cysteine, glutamate, and glycine. Metabolomic differentiation in sulfur-containing amino acids is a commonly observed phenomenon in heavy metal-stressed plants, signifying an adaptive response to heavy metals. Other common metabolites indicating

Biomarkers and Metabolomics, Evidence of Stress. Table 2 Examples of plant metabolomic studies under various stressors

Type of study	Plant	Stressor	Description	Reference
Biomarker discovery	<i>Arabidopsis thaliana</i>	Physical (heat, cold)	Accumulation of amino acid and osmolytes	[80]
	<i>A. thaliana</i>	Physical (wound)	Accumulation of oxylipins and jasmonates	[82, 83]
	<i>A. thaliana</i>	Heavy metal (Cd)	Accumulation of phytochelatins and precursors	[84]
	<i>Hordeum vulgare</i> (barley)	Salt stress	Accumulation of proline, sucrose, and glucose	[91]
	<i>A. thaliana</i>	Nutritional stress	Repression of many metabolites with reduced metabolic rates	[93]
Mode of action	<i>Zea mays</i> (corn)	Pesticides	Mode of action specific metabolomic response to 24 herbicides	[94]
	<i>Lemna minor</i>	Pesticides	Mode of action-dependent changes of amino acids and precursors	[96]
Toxicity	<i>Oryza sativa</i> (rice)	Ozone	Integrative approaches with metabolomics, transcriptomics, and proteomics	[103]
Biological stress	<i>Brassica rapa</i> (Chinese cabbage)	Insects	Differential accumulation of alanine, threonine, glucose, sucrose, feruloyl malate, sinapoyl malate, and gluconapin	[99]

adaptive changes include sugars and sugar alcohols. Plants can also modulate secondary metabolism in response to heavy metals such as copper and mercury. Jahangir et al. [85] observed an increase in the secondary metabolism and differentiation of amino acid and sugar levels in Chinese cabbage (*Brassica rapa*) when it was treated with copper, iron, and manganese. Rapid accumulation of glucosinolates (a secondary metabolite) was observed in *A. thaliana* under nutritional stresses [86]. These findings indicate that there may be a common feature of stress from exposure to heavy metal and nutrient deficiency.

High soil salinity significantly impacts plant growth and decreases crop yields. Salinity-related stresses are frequently accompanied with low water supplies in agricultural practices. The metabolic impact of salt stress was assessed on several crops and plant models (e.g., *A. thaliana*, barley, grape, rice, and tomato) [78, 87–91]. Accumulations of proline, sucrose/glucose, and inositol are the most frequently observed response

in salt-stressed plants. Another common response includes up-regulation of proteins involved in polyamine and γ -aminobutyric acid metabolism and associated metabolites. The levels of organic acids in the TCA cycle usually decrease under salt stress, which may indicate reduced cellular activity. A general conclusion from metabolomics studies of salt-stressed plants includes changes in organic acid, amino acid and sugar metabolism.

Metabolomic profiles of plants under water stress share a common feature with those under salt stress, including increased sugar content [92]. Plants are primary sources of human foods. Therefore, plant metabolism under different nutritional conditions (i.e., fertilization) is of tremendous importance. However, only a limited number of papers have been published. *A. thaliana* is the most commonly used plant model. Hirai et al. [93] studied metabolite profiles and transcriptomes of *A. thaliana* under sulfur or nitrogen limitation. Several genes and metabolites were

commonly expressed under both sulfur and nitrogen deficiencies. For example, nitrate reductase, a key enzyme of nitrogen assimilation, was down-regulated under both conditions. Reduction of this enzyme and the associated metabolites indicated that reduced metabolic rates may be a common response to nutrient deprivation. However, some metabolites such as glucosinolates were differently accumulated between nitrogen- and sulfur-deficient conditions. Metabolic consequences of sulfur-limitation in plants were further investigated by Nikiforova et al. [86]. Limited supplementation of sulfate leads to a decrease in sulfur metabolite pools (e.g., cysteine and methionine). Because these metabolites are an integral part of plant metabolism, sulfur deficiency induces a number of adaptive responses. Decreases in biomass, levels of proteins, chlorophylls, and total RNA suggest a general reduction of metabolic activity. These responses are compensated by a systemic adjustment of the major metabolic pathways. Representative responses include re-partitioning of sulfur, carbon, and nitrogen through the accumulation of metabolites.

Metabolomic investigations of pesticide effects on plants are limited. Ott et al. [94] studied metabolomic responses in corn (*Zea mays*) treated with 24 different herbicides. They successfully discriminated chemicals having different modes of action. Comparative metabolomic studies with pyrenophorol indicated that this fungal toxin may have different modes of action from the commercial herbicides used on the oat *Avena sterilis* [95]. Recently, the metabolic response of the aquatic weed *Lemna minor* was investigated in relation to herbicidal activities of glyphosate, atrazines, and other chemicals [96]. GC-MS based metabolomics of *A. thaliana* indicated that herbicides having different modes of action result in notably different metabolomes [97]. For example, sulfonylurea herbicides induced large differences in metabolite profiles, specifically those involved in glycolysis, the TCA cycle, and nitrogen assimilation. Applications of novel statistical tools in conjunction with LC-MS analysis indicated that the insecticide carbofuran can induce large changes of endogenous metabolomes in tomato fruits [98].

Interactions among plants, pest insects, and pathogens are another interesting subject of metabolomics. For example, *B. rapa* leaves, attacked by the

diamondback moth (*Plutella xylostella*) or beet armyworm (*Spodoptera exigua*), differentially accumulated alanine, threonine, glucose, sucrose, feruloyl malate, sinapoyl malate, and gluconapin, depending upon the insect species and the developmental stages [99].

Metabolomics with aquatic plants or algae are scarce, although their environmental significance is as important as their terrestrial counterparts. Representative examples include metabolomic evaluations of the green algae *Chlamydomonas reinhardtii* under nutritional stress [100, 101]. This microalga is known to produce hydrogen under anaerobic conditions. Recent studies indicated that a large portion of metabolites are differentially expressed, depending upon the deprived nutrients. Time-resolved assays suggested that the kinetic responses also differ among nutrients. For example, the response to phosphorus deprivation was slower than to sulfur or nitrogen [100]. Matthew et al. [101] found that hydrogen overproduction in *C. reinhardtii* is induced by sulfur-deprivation through metabolic re-programming or a build-up of the toxic fermentative products formate and ethanol. An excellent review has been published about metabolomic studies of marine macroalgae [102].

The most notable trend in recent plant metabolomics is integrated omics. By integrating transcriptomics, proteomics, and metabolomics, characteristic differentiation of metabolomes was identified as a defensive response in rice seedling (*Oryza sativa*) [103]. These findings provided insights into metabolic responses against stresses.

Another interesting advance in metabolomics is the development of novel data-mining technologies. Sato et al. [104] investigated rice foliage metabolomes through correlative approaches between metabolites and regulatory networks. In general, most metabolomic research gives numerical data with no correlative information among metabolites. Correlations among metabolites, genes, and proteins will give more comprehensive understanding of stress response.

Metabolomics in Microbiology

There have been a limited number of publications on metabolomics of microorganisms, particularly under stressed conditions. Microorganisms are more prone to metabolic changes than higher organisms because they

are directly exposed to the stimuli. Tweeddale et al. [105] reported that *Escherichia coli* underwent interesting metabolic changes under oxidative stress. Paraquat, a well-known respiratory inhibitor, can induce the up-regulation of several oxidative stress-related proteins and an increase of branched amino acid and sulfur-containing metabolite pools (e.g., valine and glutathione) [105].

Elucidation of mode of action is a very important subject in pesticide and drug discoveries. However, this can be a laborious and time-consuming task because a biological system contains a wide array of metabolites, proteins, and genes. Metabolomics is a high throughput, comprehensive analytical option for this purpose. The first example can be found in metabolic phenotyping of the yeast *Saccharomyces cerevisiae* mutants [9]. Metabolic patterns of *S. cerevisiae* treated with 10 commercial fungicides were differentiated via metabolomics, where two large clusters were derived according to the inhibitory activities [106]. Such a study was extended to non-model diatoms under iron starvation [107].

Heavy metals are stressors to microorganisms [107–109]. Heavy metals can induce metabolic changes in glutathione and osmolytes (e.g., glycine and betaine) as well as other metabolites. Among these metabolites, glutathione and betaine are commonly found in stressed plants, animals, and microorganisms. Recent studies with the anaerobic bacteria *Shewanella oneidensis* indicated that the overall metabolisms are highly stable even under extremely stressed conditions. Only part of the metabolic pathways (e.g., sulfur amino acid metabolism) gave rapid responses to the external toxicants [110].

Bacterial metabolomics with environmental relevance were recently reported [111, 112]. For example, the bacterium *Sinorhizobium*, upon exposure to environmental contaminants, has shown a characteristic shift to a more hydrophobic fatty acid profile. In addition, the amount of storage metabolites such as polyhydroxyalkanoates decreased under stressed conditions. A large portion of the metabolites decreased, while trehalose, branched amino acids and sulfur-containing acids accumulated. The results indicated that oxidative stresses and metabolic confinement are a response to nutritional deficiency [112].

A recent trend in microbial metabolomics is integrative omics. Intracellular metabolism of benzoic acid in the white-rot basidiomycete *Phanerochaete chrysosporium* was investigated at the proteome and metabolome levels. Up-regulation of aryl-alcohol dehydrogenase, arylaldehyde dehydrogenase, and cytochrome P450s suggested that these enzymes play key roles in benzoic acid metabolism. Intracellular metabolic shifts to the TCA cycle indicated activation of heme biosynthesis and the production of NAD(P)H. Both metabolites are the most important components of oxidative enzymes. The analyses also indicated the role of trehalose as a storage disaccharide and the presence of an alternative energy-producing pathway [113]. The bacterium *Streptomyces tenjimariensis* can produce istamycins, displaying a high potency against many Gram-negative and Gram-positive bacteria. Denery et al. [114] used metabolic profiling and polymerase chain reaction (PCR) techniques as a means of studying the growth of *S. tenjimariensis*. The study showed metabolite profiles that are unique to growth phase and signify how they can be used for further applications in the understanding of microbial metabolism, antibiotic production, and physiology.

Future Directions

Metabolomics is an emerging field. It has started to play an important role in biological sciences, particularly in systems biology and biomarker studies. However, its applications are still limited by many challenges in methodologies and applications. A noteworthy example is “lipidomics,” a branch of metabolomics focusing on lipids. A tremendous amount of research has been done with hydrophilic metabolites, whereas applications of lipidomics are very limited. It is no doubt that lipidomics will become an important tool in lipid research, particularly concerning the physiological significance and function of lipids. The metabolome is the down-stream product of genes and proteins. Metabolomics alone can give the final outcome of specific stresses, but does not provide direct information on the up-stream changes such in genes and proteins. This is both the strength and weakness of metabolomics and, therefore, integrated omics approaches seem to be inevitable. Many examples of integrated omics have recently been published, and this

approach will become more popular in the future. Such a trend will improve both the quality and quantity of metabolomic data, especially in environmental toxicology. Technological challenges include data mining, analysis, and synthesis (i.e., data dimensionality and processing). Comprehensive networks of metabolites, proteins, and genes provide an overview and in-depth understanding of biological events and processes. Metabolomics tells what is happening at the metabolic level, provides direct evidences of stress, and will therefore contribute significantly to environmental toxicology.

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Biomass as Renewable Source of Energy, Possible Conversion Routes

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Article Outline

Glossary
Definition of the Subject
Introduction
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Glossary

Biochemical conversion Conversion of biomass based on biological processes into energy carriers and/or energy.

Bioenergy Bioenergy is defined as energy from biomass.

Biofuel Biofuel is a fuel produced directly or indirectly from biomass.

Biomass From a scientific and technical point of view, biomass is defined as material of biological origin excluding material embedded in geological formations and/or transformed to fossil.

Conversion route A conversion route is defined as the overall processes of production, provision, handling, and processing biomass to the point of delivery of the useful energy.

Physicochemical conversion Conversion of biomass based on physical and/or chemical processes into energy carriers and/or energy.

Thermochemical conversion Heat induced conversion of biofuels into energy carriers and/or energy.

Definition of the Subject

Biomass, a renewable source of energy, has been used since the beginning of human culture. Until the introduction of coal, crude oil, and natural gas, wood and other forms of biomass were the most important sources of energy available to humans. Today, biomass accounts for roughly 10–12% of the global primary energy consumption and, at a time of politically forced and environmentally needed greenhouse gas mitigation and an expected shortage in fossil fuel energy resources, this energy carrier is becoming more and more important. The goal of this chapter is to give an overview of the technical possibilities and challenges of energy provision from biomass. First, the various biomass sources available are discussed briefly. Next, available conversion routes are presented, showing the broad variety of possible options to provide heat, electricity, and/or transportation fuels. Based on these fundamentals, the thermochemical, physicochemical, and biochemical conversion possibilities are discussed. For these three options, in addition to the basics, the technical possibilities are briefly presented to indicate the current status of technology. Finally, future directions are discussed.

Introduction

Biomass currently provides 10–12% of global primary energy. Due to geographical, economic, ethical, and climatic differences, as well as different frame conditions within the energy system, the share of bioenergy in relation to the total energy consumption differs widely between different countries, ranging from less than a few percent in some industrialized countries like the United Kingdom to significantly more than 50% in some developing countries in Africa and Asia. Nevertheless, biomass is by far the most important

renewable energy source in most countries, being significantly larger in use than the second largest source, hydropower. The energy from these sources – the oldest fuels utilized by humans – is even larger in absolute terms than the energy from one of the newest – nuclear fuels.

Solid biofuels dominate the global biomass picture. It is safe to say that significant shares of the world's population still rely on solid biofuels for most of their energy. This situation has not changed since the mastery of fire some hundred thousand years ago. This is due to the relatively low cost of and easy access to solid biofuels such as wood, dried dung, and crop residues (like straw) in rural areas of developing countries where more than one third of humanity lives. In addition, other bioenergy carriers such as wood pellets, bioethanol, and biogas play an increasingly important role in some regions in developing as well as in industrialized countries, where their costs and access compare favorably with fossil fuel-based energy in the context of the frame conditions defined by the respective governments. Additionally, the potential of the biomass resources available to humans is significant on a worldwide scale. Sustainably produced solid, liquid, and/or gaseous biofuels also have the advantage of being climatically neutral and environmentally sound compared with other sources of fossil fuel energy, which has led to a resurgence in interest in biomass throughout the world.

Compared with other renewable sources of energy, biomass has the advantage that it can be used for heat provision, electricity production, and the provision of liquid and gaseous fuels for transportation purpose. And within all of these markets, biomass already plays a certain and increasing role within the global energy system. This development will accelerate in the years to come, with an increasing energy price level.

Heat from biomass is used for cooking and/or space heating. While cooking with (solid) biofuel is rare today in industrialized countries (with the exception of outdoor barbecue), this is still the “classical” bioenergy application in most developing and threshold countries. It is likely that this market will continue to grow in the years to come due to a significant increase in population, especially in these countries. Heat provision from biomass for domestic and industrial applications is realized in all countries worldwide,

but generally more in rural areas of countries during the cold season. This heating market is also likely to grow in the future, especially if crude oil prices continue to stay relatively high or increase further. Additionally, due to the political goal to reduce greenhouse gas emissions and the development of highly efficient and more comfortable combustion technologies, heat provision from solid biofuels is undergoing a renaissance in some industrialized countries.

Demand for electricity has increased greatly in recent years in all countries. Even though the use of electricity is widely accepted, the provision of electrical energy can be controversial in some countries with a strong environmental movement. The debate about the pros and cons of nuclear power and the discussion about the contribution of electricity from hard coal and lignite to the global greenhouse effect are only two examples. Therefore, the generation of electricity from biomass is seen in some countries as a promising alternative, contributing in parallel a more indigenous and safer electricity provision, as well as increasing prosperity in rural areas. For this reason, it can be expected that the production and provision of electricity from biomass will significantly increase in the years to come. Within combined heat and power (CHP) plants, electricity generation can be combined in an ideal way with heat provision by maximizing the overall energetic efficiency. With limited available biomass resources, this option is gaining more importance, especially in countries with a high heat demand due to cold winters. For this reason, a considerable and growing share of the increasing electricity production from biomass is realized in CHP plants, depending on the frame conditions set by the respective government.

Production of transportation fuels from biomass is also increasing. The need for mobility is dramatically growing on a worldwide scale, particularly in some of the emerging economies in Asia. Therefore, finding ways to provide cheap, technically mature, climatically sound, and environmentally benign fuels based on renewable energy in general and biomass in particular is an extremely active endeavor. Therefore, the research and development (R&D) activities in this field have increased significantly in recent years in most of the Organization for Economic Co-operation and Development (OECD) countries, as well as in selected developing countries and emerging economies; the

main challenge is to produce more liquid and/or gaseous transportation fuel from the limited available biomass. This challenge is the same worldwide, but, so far, only Brazil and the United States produce liquid biofuels (ethanol) for transportation purposes on a large scale with a measurable impact within the energy system.

In the following sections, the available biomass resources are discussed, and the various conversion routes of biomass – thermochemical, physicochemical, and biochemical – into useful energy will be described.

Biomass Sources

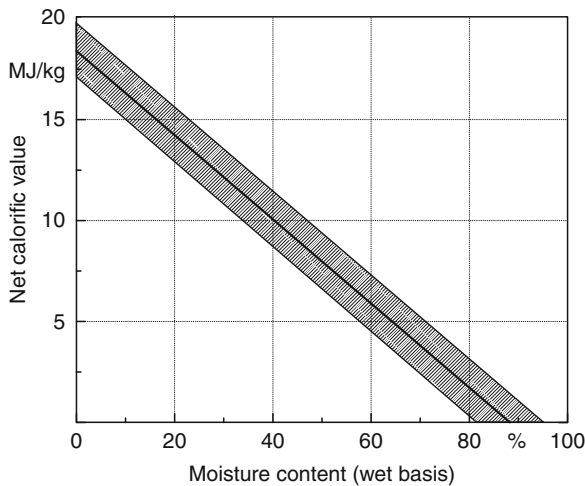
Biomass consists primarily of the elements carbon (C), hydrogen (H), and oxygen (O) (Table 1). Additionally, significant amounts of trace elements can be found in some types of biomass. For example, straw may contain fairly high amounts of chlorine (Cl) and/or silicon (Si) and rapeseed contains a relatively high amount of nitrogen (N). These trace elements can sometimes cause problems during the conversion into an energy carrier and/or useful energy. For example, during combustion chlorine might cause high temperature corrosion in boilers, silicon can lead to boiler slagging, and nitrogen can be responsible for high NO_x emissions, which are limited in most countries.

In most practical applications, the energy content of biofuel is best described by the net calorific value. Besides the chemical composition of the organic material, net calorific value is influenced by the water content of the biomass. Due to the fact that the chemical composition of most solid biomass fractions does not vary significantly (Table 1), the net calorific value related to the dry matter is similar for most of the biomass streams used (e.g., wood, straw) for the provision of solid biofuels. This might be different for liquid or gaseous fuels provided by a more or less complex conversion process based on heat-induced (i.e., thermochemical conversion) and/or biological processes (i.e., biochemical conversion).

Figure 1 shows that the net calorific value of wood decreases from approximately 18.5 MJ/kg dry matter with increasing water content. The net calorific value is zero at water content of approximately 88%. Normally, the water content of air-dried wood is between 12%

Biomass as Renewable Source of Energy, Possible Conversion Routes. Table 1 Energy content and concentrations of some elements in untreated biomass (various sources, e.g., [1])

Type of biomass	Net calorific value in MJ/kg	Ash content in %	Volatile compounds in %	C	H	O	N	K	Ca	Mg	P	S	Cl
				in % of dry substance									
Spruce wood (with bark)	18.8	0.6	82.9	49.8	6.3	43.2	0.13	0.13	0.70	0.08	0.03	0.015	0.005
Beech wood (with bark)	18.4	0.5	84.0	47.9	6.2	45.2	0.22	0.15	0.29	0.04	0.04	0.015	0.006
Poplar wood (Short rotation)	18.5	1.8	81.2	47.5	6.2	44.1	0.42	0.35	0.51	0.05	0.10	0.031	0.004
Willow wood (Short rotation)	18.4	2.0	80.3	47.1	6.1	44.3	0.54	0.26	0.68	0.05	0.09	0.045	0.004
Bark (softwood)	19.2	3.8	77.2	51.4	5.7	38.7	0.48	0.24	1.27	0.14	0.05	0.085	0.019
Rye straw	17.4	4.8	76.4	46.6	6.0	42.1	0.55	1.68	0.36	0.06	0.15	0.085	0.40
Wheat straw	17.2	5.7	77.0	45.6	5.8	42.4	0.48	1.01	0.31	0.10	0.10	0.082	0.19
Triticale straw	17.1	5.9	75.2	43.9	5.9	43.8	0.42	1.05	0.31	0.05	0.08	0.056	0.27
Barley straw	17.5	4.8	77.3	47.5	5.8	41.4	0.46	1.38	0.49	0.07	0.21	0.089	0.40
Rape straw	17.1	6.2	75.8	47.1	5.9	40.0	0.84	0.79	1.70	0.22	0.13	0.27	0.47
Corn straw	17.7	6.7	76.8	45.7	5.3	41.7	0.65					0.12	0.35
Sunflower straw	15.8	12.2	72.7	42.5	5.1	39.1	1.11	5.00	1.90	0.21	0.20	0.15	0.81
Hemp straw	17.0	4.8	81.4	46.1	5.9	42.5	0.74	1.54	1.34	0.20	0.25	0.10	0.20
Rice straw	12.0	4.4											
Husk	14.0	19.0											
Rye whole crop	17.7	4.2	79.1	48.0	5.8	40.9	1.14	1.11		0.07	0.28	0.11	0.34
Wheat whole crop	17.1	4.1	77.6	45.2	6.4	42.9	1.41	0.71	0.21	0.12	0.24	0.12	0.09
Triticale whole crop	17.0	4.4	78.2	44.0	6.0	44.6	1.08	0.90	0.19	0.09	0.22	0.18	0.14
Rye grain	17.1	2.0	80.9	45.7	6.4	44.0	1.91	0.66		0.17	0.49	0.11	0.16
Wheat grain	17.0	2.7	80.0	43.6	6.5	44.9	2.28	0.46	0.05	0.13	0.39	0.12	0.04
Triticale grain	16.9	2.1	81.0	43.5	6.4	46.4	1.68	0.62	0.06	0.10	0.35	0.11	0.07
Rape grain	26.5	4.6	85.2	60.5	7.2	23.8	3.94					0.10	
<i>Miscanthus</i>	17.6	3.9	77.6	47.5	6.2	41.7	0.73	0.72	0.16	0.06	0.07	0.15	0.22
Switchgrass													
Sugar cane stalk (bagasse)	8.0	4.0	80	45	6.0	35	0.0					0.0	
Hay from various sources	17.4	5.7	75.4	45.5	6.1	41.5	1.14	1.49	0.50	0.16	0.19	0.16	0.31
Roadside greenery	14.1	23.1	61.7	37.1	5.1	33.2	1.49	1.30	2.38	0.63	0.19	0.19	0.88



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 1

Net calorific value of wood depending on the moisture content [1]

and 20%, yielding a calorific value between 13 and 16 MJ/kg. Freshly harvested wood is characterized by a water content of about 50% or more. A significantly lower net calorific value is the result. This is the reason why wood is usually dried with solar energy.

Independent of the fact that the heating value is more or less similar for organic matter used for the provision of solid biofuels, there is a huge variety of different biomass material streams available to be used as a source of energy. The properties of these biomass fractions define the conversion routes that are technically possible and economically feasible. The most important biomass fractions are discussed below.

Woody Biomass

Wood is the “classical” solid biofuel, used for thousands of years (basically since the mastery of fire by humans). This is especially true for wood from forests. In most countries fire wood as an energy carrier is a product from forestry management like timber for the use as a raw material (e.g., for construction purpose). In addition to forest wood, woody biomass to be used as a source of energy can also be grown on agricultural land. To maximize the average yield and thus minimize the land needs, tree plantations are harvested

after a couple of years (i.e., short rotation coppice). Beside this, wood fuel can be derived from production and consumption of wood and wood products as a residue, a by-product, and/or a waste material all along the supply chain of wood as a raw material as well as pulp and paper products (Fig. 2). For example, thinning wood and forest residues are produced as a by-product during the production of stem wood as a raw material for case goods and furniture production. Industrial residual wood, bark, and wood dust are by-products and/or waste materials resulting from the production of timber and the manufacturing of wood structures or wood products. At the end of the product lifetime and after recycling of some wood fractions (such as old furniture or roof timbering, chipboards), partly contaminated woody material and waste wood remain, which can be used as fuel.

Herbaceous Biomass

The available organic material flow from herbaceous biomass can be subdivided into herbaceous energy crops grown specifically as biomass fuels (like whole crop cereal, rape or sunflower seed, *Miscanthus*, switchgrass, sugar cane, maize silage) and by-products of the production of non-energy products (like straw produced during the production of cereals). The latter arise primarily from the production processes for the provision of food, fiber, and fodder (e.g., the production of grain is necessarily connected with the production of straw). The same is true for the production of crops with special substances (e.g., specific oily substances, specific scents) to be used as a raw material (e.g., in the chemical industry, for the production of pharmaceuticals). Additionally herbaceous biomass is also produced, for example, in conservation areas, parks, cemeteries, gardens, and on roadside areas.

Other Biomass

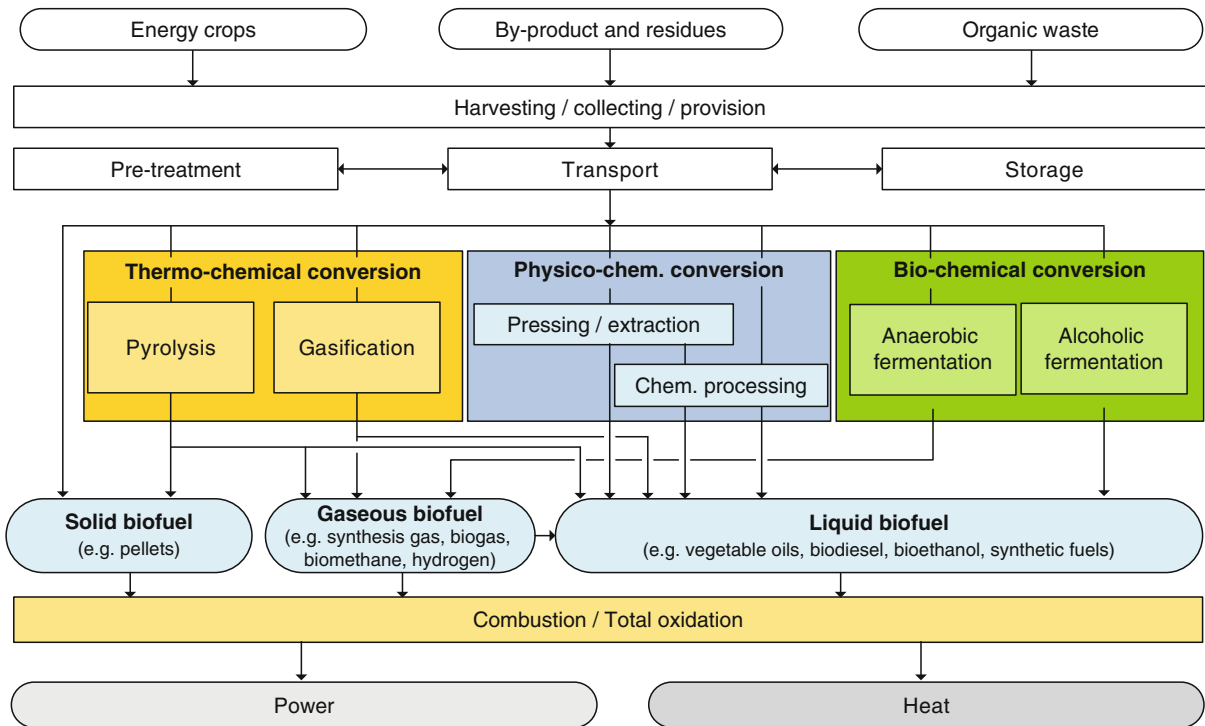
Various other organic materials usable as a source of energy are available within the overall economy, including by-products and waste materials from agriculture (e.g., animal manure), industrial food and fodder processing processes (e.g., slaughterhouse residues, vegetable waste, olive and fruit pits), food



Material flow of wood within the overall economy [1]

Conversion Routes

The different possibilities to provide secondary energy carrier with more promising fuel characteristics compared with mechanically treated biomass (like wood chips, wood logs, pellets, silage, organic waste) can be subdivided in options based on heat induced processes (i.e., thermochemical conversion), on biological processes (i.e., biochemical conversion), and on physico-chemical processes (physicochemical conversion). These



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 3

Possibilities to provide heat and/or power from biomass (Based on [1])

different options are discussed briefly below. But before that the provision of biomass free conversion plant is analyzed.

Design of Typical Conversion Routes

In general, the conversion route describes the pathway from the production of the energy crops, the provision of residues, by-products, and/or wastes at the place of origin until the provision of the biomass in a predefined form at the gate of the conversion plant, the provision of secondary energy carrier (e.g., solid, liquid, or gaseous fuel, district heat), the provision of final energy (e.g., heat, electricity), or the provision of useful energy (e.g., heat, power). Thus, such a conversion route describes the overall life cycle from the production respectively the come up of the organic matter (i.e., the primary energy) up to the provision of the secondary, useful, or final energy.

The overall goal of such a conversion route is to meet a varying demand of final or useful energy with a predefined security of supply. To reach this goal, appropriate conversion plant(s) with a reliable technical performance are needed as well as the necessary amount of biomass of a predefined quality.

Each conversion route consists of the life cycle steps of biomass production, and each of these steps is composed of various single technical processes. For example, biomass production requires preparation of the seed bed, distribution of fertilizer as well as plant protecting agents, and selected cultivation measures.

Because the different life cycle stages of a biomass conversion route normally do not take place at the same location, the distances have to be travelled by various means (e.g., trucks, pipelines, conveyor belts). The choice of transportation is – beside technical aspects – mostly based on economic considerations.

A specific conversion route is thus very much defined by the frame conditions fixed by the available biomass

(supply side) on the one hand and the requested provision of the final and/or useful energy (demand side). Additionally, technical, economic, and environmental (as well as administrative and/or legal (and emotional)) aspects significantly influence the realization of such a conversion route. For example, the choice for a specific conversion technology is influenced by the desired final or useful energy carrier (e.g., thermal energy, mechanical energy, electrical energy) and the (cheap) locally available biomass. The environmental standards defined by governments (e.g., emission limits, noise limits, odor regulations, waste disposal directives) and the economic frame conditions pertaining to the specific circumstances define the design and practical realization of such a biomass conversion route. Additionally, the disposal of waste produced by different processes within the overall route (e.g., digested animal manure leaving the biogas plant, ash remaining after the combustion of wood pellets) might influence the layout of such a route dramatically. Based on the consequences resulting from the thus necessary (expensive) waste disposal, a certain demand could be formulated to the quality of the biomass (e.g., water content, dimensions, impurities) used within such an overall conversion route. To achieve the desired effects, the quality of the used biomass has to be guaranteed within the overall route, with the consequence that there might be the need to include additional processing steps in the provision chain.

Biomass availability can vary throughout the different seasons of the year, which has to be taken into consideration as energy demand changes over time. This means that certain storage options (e.g., wood chip storage, heat storage) have to be included within the overall chain to ensure a predefined degree of security of supply.

Additionally, the developed conversion route matching all these demands has to be economically viable under the frame conditions defined by the investor, the local frame conditions, and the government, have the opportunity to receive the required legal authorization (if applicable), and – last but not least – be socially and emotionally acceptable to the people living close to the conversion plant. And – which makes the design, successful operation, and ongoing optimization of such a conversion route even more challenging – different players with different backgrounds and understanding (like farmers, power plant operators,

investors) have to communicate and interact successfully with each other as well as with the representatives of the (local) regulatory authority. Thus a biomass conversion route is defined by technical as well as various nontechnical aspects. This makes the set-up of new chains exiting and demanding.

Conversion Options to Provide Secondary Energy Carriers

The conversion of biomass (i.e., organic material of very different origin) into solid, liquid, and/or gaseous secondary energy carriers can be realized via heat-induced processes (i.e., thermochemical conversion), via transformation by bacteria (i.e., biochemical conversion), and/or via physicochemical processes. These conversion processes are, in most cases, the “heart” of such a conversion route. Below, an overview is given to explain the most important possibilities as well as the main differences.

Thermochemical conversion. Biomass can be converted into useful energy or into secondary energy carriers using conversion processes based on heat.

During the “classical” combustion of biomass for the provision of heat and/or electricity, the biomass is fully oxidized, basically with oxygen from the surrounding air, by releasing heat. Various chemical processes are realized during this oxidization. These processes take place in parallel at the same place. Due to the frame conditions defined by the involved combustion technology and its defining control parameters, the chemical reactions can be influenced to a certain degree to minimize the creation of unwanted substances harmful to the environment.

Alternatively, the thermochemical conversion can be split up and realized at different places. Within such conversion processes, solid biomass is mixed under defined conditions (pressure, temperature, etc.) and high temperatures with an oxidizing agent (e.g., air, water) clearly below the stoichiometric concentration. This enables them to be converted into solid, liquid, and/or gaseous secondary biofuels to be used somewhere else. The chemical processes underlying the respective conversion routes are based on the same fundamental reactions. But the composition of the resulting secondary energy carrier varies depending on, for example, the involved technology, the selected

process parameters, the catalyst involved (if applicable), and the type of biomass used.

In gasification, the solid biofuels are converted as completely as possible into an energy-rich producer gas or synthesis gas and thus into a gaseous secondary energy carrier. After expensive cleaning processes, the gas can be used directly without any further chemical transformation, for example, in an engine, a turbine, or even a fuel cell to provide heat and/or electricity. Alternatively, the gas can undergo a subsequent synthesis process to be converted into a liquid or gaseous biofuel with clearly defined properties (e.g., Fischer-Tropsch diesel, synthetic natural gas (biomethane), hydrogen) for easy use within the transportation sector, for example.

In pyrolysis, solid biomass is converted solely by the (short- or long-duration) application of heat into solids (charcoal), liquids (bio-crude oil), and gases (e.g., CO, H₂, CO₂).

- The aim of fast pyrolysis or intermediate pyrolysis processes is to obtain a maximum yield of liquids (i.e., bio-crude oil). The by-products – e.g., combustible gases and charcoal – can be used to provide the energy needed for the conversion process and/or as a raw material (e.g., active coal as a filter medium). The produced pyrolysis oil or bio-crude oil has to be refined and can then be utilized either as feedstock for the chemical industry and/or as liquid fuel for engines and/or turbines.
- The goal of slow pyrolysis processes is it to convert solid biomass into a solid energy carrier with clearly defined characteristics (i.e., charcoal) and thus improved combustion characteristics compared to the feedstock. This solid carbon can then either be used as a more pleasant source of energy (e.g., for daily cooking in developing countries and for leisure activities (barbecue) in industrialized countries) or as a raw material, for example, in the chemical industry (e.g., as a filter material).

Thus, based on such a thermochemical conversion – besides the provision of heat and electricity – the direct and/or indirect production of solid, liquids and/or gaseous secondary energy carriers is also possible.

Physicochemical conversion. This conversion pathway is used to produce liquid biofuels from organic matter containing oils and fats (e.g., rapeseed,

oil palm fruits, sunflower seeds). The oil is separated from the seed, for example, by pressing and/or extraction based on existing process technology well known for centuries. Afterwards the oil is cleaned with existing technical processes to meet the given predefined product standards. The clean vegetable oil can be used as an energy source in its straight form (if the engine is able to burn such a relatively inhomogeneous fuel characterized by considerable differences from conventional diesel fuel) or after a chemical treatment conversion (e.g., transesterification with methanol to fatty acid methyl ester [FAME]). Alternatively, the vegetable oil can be treated with hydrogen (i.e., hydrogenation to hydrogenated vegetable oil [HVO]) or processed together with crude oil in existing oil refineries to provide a fuel with clearly defined characteristics meeting the requirements for the existing transportation fuels (e.g., diesel fuel specification, kerosene specification).

Biochemical conversion. In this group of conversion processes using microorganisms, organic material is split into fragments that could be used to provide new chemical compounds. Hence, this conversion is based on biological processes.

- During alcoholic fermentation, the sugar, starch, and cellulose contained in some types of biomass is transformed into ethanol, which, after distillation and dehydration, can be used as pure alcohol or blended with conventional gasoline to fuel engines and/or turbines.
- In anaerobic fermentation, organic matter is converted into biogas (slightly more than 50% methane; the rest is mainly carbon dioxide). This gas can be used in CHP generating stations to produce electricity and heat or, alternatively, after further processing, upgrading, and where necessary distribution through the existing natural gas grid, used to fuel vehicles designed to use of natural gas.
- Other biochemical conversion options currently under discussion include the production of, for example, hydrogen from some specific types of organism living in an aqueous environment.

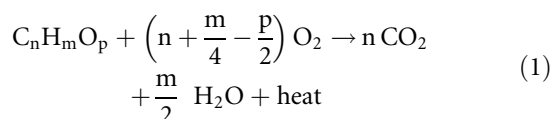
Thermochemical Conversion

Thermochemical conversion describes the conversion of preferably solid biofuels into secondary energy

carriers, into final energy, and/or into useful energy based on heat-induced processes. For this conversion option, the chemical basics are discussed below. Then, the solid biofuels usually used within such conversion units are briefly described. The technologies for direct combustion, pyrolysis, and gasification are then presented.

Basics

During the complete thermochemical conversion, solid biofuels are oxidized primarily to carbon dioxide and water by releasing heat. Equation 1 shows the approximate process for wood, which can be described chemically as $C_nH_mO_p$.



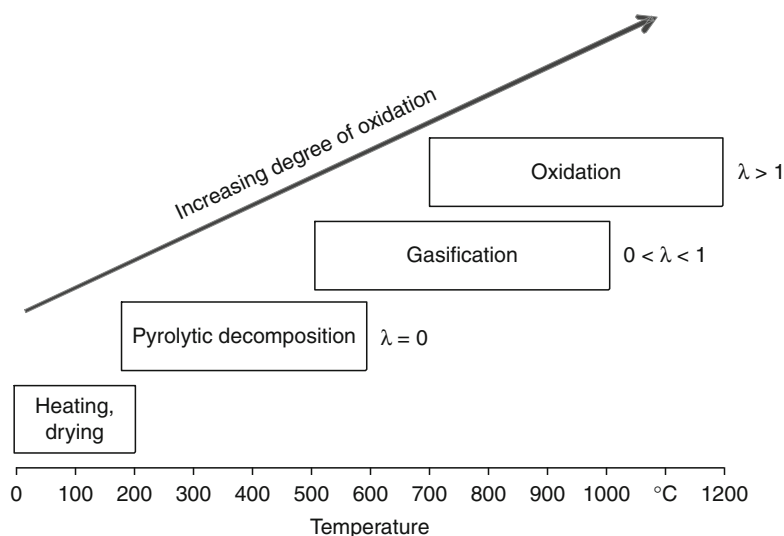
The complete thermochemical conversion of solid biofuels consists of the following steps: heating and drying, pyrolytic decomposition, gasification, and oxidation (Fig. 4). Within a “classical” biomass combustion unit for heat provision, these four different thermochemical conversion steps are realized at the same place and at the same time. Equation 1 is

performed – via different intermediate steps as discussed below in detail – completely (i.e., full oxidation).

Alternatively to overall oxidation (Eq. 1) can be split and performed at different points of time and in various locations. For example, such an interruption can be realized after the steps of heating and drying as well as pyrolytic decomposition; gasification and oxidation take place within another device (i.e., in a different place) and at a different point in time. Another possibility is it to split the process after three intermediate conversion steps (i.e., heating and drying, pyrolytic decomposition, and gasification).

These different steps of the thermochemical conversion are explained below.

Heating and drying. Before any chemical reaction of the organic material (e.g., wood, straw, rice husks) can take place, the biomass has to be heated up. During this endothermic process, water is evaporated at temperatures up to approx. 200°C. Below roughly 100°C free water, and above this temperature, water bound to the molecule structure of the solid biomass, is released as vapor. The water may leave the organic material and thus the reaction zone. Alternatively and/or additionally, this water vapor may act as an oxidizing agent within the processes taking place within subsequent



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 4
Processes realizing the thermochemical conversion of solid biofuels [1]

conversion steps (e.g., gasification). This process of heating and drying requires energy (i.e., the process is endothermic).

Pyrolytic decomposition. Organic material consists of large macromolecules. If they are sufficiently exposed to thermal energy they are thermally decomposed in smaller chemical molecules (i.e., chemical compounds with only few elements). The products of this pyrolytic decomposition of the solid biomass (i.e., the so-called volatile compounds) are driven out of the organic material. This process is endothermic (i.e., energy is needed) and requires no oxygen.

For example, for wood the pyrolytic decomposition starts at about 200°C with the decomposition of hemicellulose, which is a part of wood material. The decomposition of cellulose (another component of wood) takes place at temperatures of 300°C and higher. Finally the decomposition of lignin (another component of wood) takes place at even higher temperatures. The yield and composition of the volatiles vary depending on the temperature and velocity at which the pyrolytic decomposition is realized. Additionally, the composition of the solid organic material (e.g., wood, straw, leaves) might have an influence overlaid by possible catalytic effects. In general, however, the result of the pyrolytic decomposition is very much the same for different types of solid biomass under comparable process conditions.

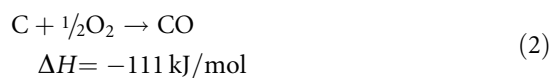
During this process, the macromolecules that biomass consists of are fragmented due to the influence of the heat by a similar set of complex decomposition reactions. As a result of such decomposition processes at relative high temperatures, the following components are formed:

- Volatile compounds, such as hydrogen (H₂), carbon monoxide (CO), methane (CH₄), carbon dioxide (CO₂), nitrogen (N₂) and steam (H₂O)
- Carbon rich solid fraction (char)
- Low molecular weight organic compounds and high molecular weight (condensable) compounds (i.e., liquid products)

Gasification. In order to convert the solid carbon remaining after the pyrolytic decomposition into a gas, an oxygen containing gasification agent such as air, pure oxygen, or water is required. Based on this, at temperatures between 700°C to 1,500°C, the solid

carbon as well as gaseous products (CO, H₂, CH₄) are oxidized as follows (Eqs. 2–6):

Partial oxidation of solid carbon:



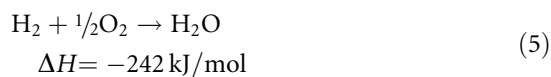
Complete oxidation of solid carbon:



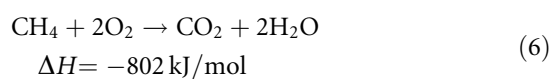
Oxidation of carbon monoxide:



Oxidation of hydrogen:



Oxidation of methane:

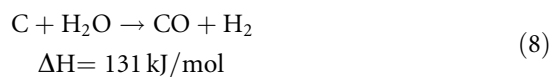


Additionally, balance reactions take place. The most important are the reduction of CO₂ to CO (Boudouard reaction) and of H₂O to H₂ (heterogeneous water gas reaction). Also, carbon can be transformed to CH₄ (Eqs. 7–9).

Boudouard reaction:



Heterogeneous water gas reaction:



Heterogeneous methane production:



These and other reactions take place during this gasification conversion step. Depending on the given conditions within the reaction zone (i.e., temperature level, pressure, gasification agent, catalyst (if applicable),

gasification technology), different chemical reactions might contribute in a varying share to the overall gasification. The consequence is that the composition of the gas might be different. Therefore, the gas composition can be influenced to a certain degree by setting the frame conditions within the reactor where these reactions are taking place. For these reasons, during gasification, sometimes energy is needed and sometimes energy is released.

Additionally, some of these reactions can also take place during the pyrolytic decomposition at higher temperatures because the biomass itself contains oxygen. Therefore, the borderline between these two conversion steps can not always clearly defined.

Oxidation. Within this last step of the thermochemical conversion, the gaseous products produced during the previous steps are fully oxidized to carbon dioxide and water. In this chemical reaction, energy is released (i.e., they are exothermic). After the performance of this step, Eq. 1 showing the overall reaction equation is fully realized. At this point the biomass is fully oxidized. Under these conditions, the excess air ratio is 1.0 or above (the excess air ratio is defined as the ratio between the amount of oxidizing agent fed to the conversion process and the amount of oxidizing agent needed to fully oxidize all reaction products; per definition the excess ratio is 1.0 if the conversion process is realized exactly stoichiometrical as shown in Eq. 1).

Solid Biofuels

For thermochemical conversion processes, usually solid biomass is available on the local, regional, and/or global markets. To allow for a highly efficient and an environmentally sound conversion, they should match easily and reliably the needs of the conversion units (and vice versa).

Based on this precondition for sustainable biomass use, two approaches are possible: (a) solid biofuels with very narrowly defined and preferably standardized fuel characteristics and (b) solid biofuels with very low respectively no requests on the fuel characteristics (i.e., no standardized fuel characteristics). The former option has the consequence that a high technical and thus resulting economic effort is needed to provide such clearly defined solid biofuels (as is the case for wood pellets). The advantage is that the fuel

characteristics can be adapted accurately to the specification of a specific type of conversion units (and vice versa). For the latter possibility, it is exactly the other way around. Here, the effort to produce the fuel is in general relatively low (e.g., manually produced wood logs, shredded demolition wood). Thus, the technical effort within the conversion plant is significantly higher because it is technologically more demanding to convert fuels with strongly varying fuel characteristics efficiently, securely, economically, and environmentally sound into useful energy compared with the former option.

The choice of which combination will be realized on the market is influenced by the user group, the installed capacity, the environmental demands defined by the responsible legal body, the economic frame conditions, the required comfort level, and the competing energy carrier as well as manifold other reasons.

For the reasons outlined above, currently the following different types of solid biofuels can be found on the local, regional, and global biofuel market.

- **Wood logs.** Wood logs are the “classical” fuel for small-scale heat application in rural areas. The fuel characteristics vary in a relatively wide area and thus the combustion unit has to be designed to ensure that nevertheless a highly efficient combustion is possible meeting local environmental standards. This fuel is mostly traded locally or on a regional basis. Often the fuel is produced by the user itself with a high amount of manual labor.
- **Wood chips.** Wood chips are a bulk fuel characterized by a higher uniformity of the fuel properties compared to wood logs. The consequence is that the production and provision is more technologically demanding. On the other hand – also in opposite to wood logs – a fully automatic production and provision from the forest to the gate of the combustion device is possible. This is also true for use within a conversion unit allowing for a fully automatic operation with a high overall efficiency meeting high environmental standards. Generally, wood chips are used in large-scale units and are traded as an energy carrier mainly on a regional basis.
- **Wood pellets.** Pelletized wood as a bulk material shows very sharply defined and uniform fuel characteristics. To achieve such standardized fuel

properties, a comparably high technical effort (compared to wood chips and especially to wood logs) is needed. This makes the production technologically demanding and the fuel relatively expensive. But such a pelletizing of wood allows for a completely mechanized fuel provision throughout the overall provision chain and a fully automatic fuel provision and use within the conversion plant. And the conversion unit can be adapted in an optimal way to the fuel characteristics. Therefore, this fuel is used in small-scale units for heating purpose as well as in very large units together with coal (i.e., co-combustion). The fuel is traded internationally.

- *Other solid biomass fuels.* In addition to the three groups of wood fuels covering an important part of the globally used solid biofuels, other biomass-based solid fuels are used in some niche markets. This is true, for example, for demolition wood, straw, coconut shells, dried dung, road side green, and dried sewage sludge processed to specific fuels (like straw bales, crushed demolition wood, sewage sludge pellets). These types of solid biofuels can only be used environmentally if the provision chain and especially the conversion unit is fully adapted to the fuel characteristics. Therefore, such special fuels are mostly used on a regional basis, partly under very specific circumstances and/or frame conditions (e.g., dried dung as a solid fuel in India because of a lack of wood fuel, sewage sludge in co-combustion with lignite in large-scale power plants to get rid of this material for environmental reasons, demolition wood in Sweden for greenhouse gas reduction reasons).

Direct Combustion

The thermochemical conversion of solid biofuels produced from biomass into heat is called combustion (i.e., the simultaneous performance of the conversion steps of heating and drying, pyrolytic decomposition, gasification, and oxidation). The heat released during the fully oxidation of the organic material can be used directly at the conversion plant (e.g., for cooking, space heating) or can be transported by means of a heat carrier (i.e., hot water, steam) to the place of consumption (e.g., district heating systems, heat distribution system within a dwelling house). The thermal energy

can also be converted via a steam turbine or by co-generation (also known as combined heat and power (CHP) process) into electricity and low temperature heat. Because of economic limits, only relatively low conversion rates of biomass fuel energy into electrical energy (maximum of 30–35%) are possible at present in typically realized biomass plants due to economic constraints. Therefore, biomass co-firing in modern, large-scale coal power plants with efficiencies up to 45% is regarded as a cost-effective option for the use of solid biofuels if the goal is only the provision of electrical energy. In addition, the use of CHP could increase the overall conversion efficiency significantly to roughly 80% and even more by lowering the electricity generation efficiency slightly. The obstacle preventing an increased use of such highly efficient CHP systems based on solid biofuels is the often missing heat sink characterized by a high demand throughout the overall year (i.e., 8,000 full load hours) and/or the nonexistent (expensive) heat distribution infrastructure.

The conversion technology required to realize a full combustion of the solid biofuel depends on the installed capacity, the fuel consistency, water content within the solid fuel, the ash melting behavior, trace elements contaminants, and many other factors. Where these conditions vary unexpectedly (the conversion plants are designed for a specific fuel with clearly defined characteristics), for example, with changeable mixtures of biomass species in the feed, performance of the conversion plant will inevitably suffer.

Modern combustion devices are designed to realize a spatial separation between the thermochemical conversion process heating and drying, pyrolytic decomposition, and gasification as well as the full oxidation of the released gases into CO_2 and H_2O . The former is realized by primary air feed into the glowing fire and the latter through secondary air feed preheated into the burning gas released by the glow, preferably in a relatively hot after-burning chamber. To achieve low unwanted airborne emissions, especially of volatile organic compounds (VOC; i.e., the typical smell of combusted wood), good mixing of air and combustible gas at high temperatures as well as a sufficient residence time of the gases within the hot zone to allow them to be fully oxidized are necessary. Additional design features assist in reducing particulate matter emissions, including those for keeping flue gas velocities low in

some specific places within the combustion unit so that ash particles can settle down and thus are not entrained.

Table 2 gives an overview of combustion technologies primarily used in industrialized countries. The characteristics of a few major systems are discussed in more detail below.

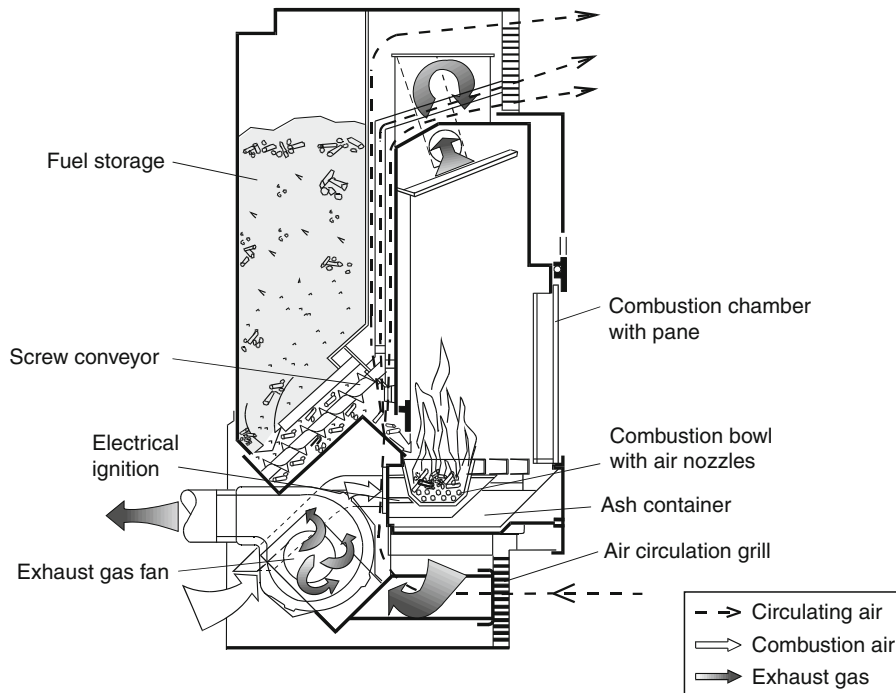
Wood pellet stove. One example of such combustion technologies are automatically feed wood pellet stoves. These combustion devices have been developed throughout the last decades for standardized pellets. On the back side of the device for the provision of heat (e.g., for a living room; Fig. 5), a container is located to store the solid fuel for automatic operation over a certain period of time. The pellets are transported from this storage facility via a screw to a pipe from where the wood pellets fall into a special designed combustion chamber. Primary air is fed by nozzles through the bottom of this combustion bowl. Preheated secondary air is blown above the burning fuel via ring-shaped nozzles to ensure the complete oxidation of the gaseous fuel components released by the glow into CO₂ and H₂O. Additional air is feed into the system via the fall pipe to prevent fire flashback into the fuel container.

This design allows achieving very low airborne emissions. It fulfills even the very strict emission regulations valid in some European countries. The ash produced during the combustion of the wood pellets is collected within an ash container to be removed and drained off manually. During ordinary operation the combustion residues (i.e., ashes) contain less than 1% carbon and can thus be used as a fertilizer or taken to a landfill depending on the legal regulation.

The thermal efficiency of such systems can reach 95% or more. Emissions are considerably lower compared to “classical” stoves fired with wood logs because the design of the combustion device is optimal adjusted to the standardized and well-defined characteristics of the pellets. Additionally, the fully automatic control system allows for a plant operation within the most efficient point of operation. This ensures that the conversion efficiencies are maximized. Also, a continuous, fully automatic operation is possible and in most cases realized; the operational comfort is basically comparable with a boiler operated with light heating oil or even natural gas. Such heating ovens can be operated over a wide range of power demands, that is, between approx. 30% and 100% of the rated capacity.

Biomass as Renewable Source of Energy, Possible Conversion Routes. Table 2 Typical combustion technologies and their characteristics

	Combustion technology	Typical thermal capacity	Biofuels
Manually fed systems	Open/closed chimney	2 to 15 kW	Wood logs, wood briquette
	Single stove	3 to 12 kW	
	Tiled stove	2 to 15 kW	
	Pellet stove	3 to 10 kW	Pellets
	Wood log stove	10 to 500 kW	Wood logs, wood briquette
Automatic fed systems	Gasification firing system	20 kW to 2 MW	Wood chips
	Under feed system	20 kW to 2 MW	Wood chips, wood shavings and filings
	Grate firing system for wood	150 kW to 15 MW	Wood, bark
	Fluidized bed system	From 10 MW	Wood, bark, sewage sludge, black liqueur
	Grate firing system for herbaceous biomass	50 kW to 20 MW	Bales, chipped herbaceous biomass
	Blow in firing system	200 kW to 50 MW	Dust, shavings and filings



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 5
Combustion device fired with wood pellets [1]

Wood chips combustion unit. A typical example for a heating device for wood chips is equipped with a throw-charging system where wood chips are transported from fuel storage with a stoker scroll and thrown with the help of a centrifugal wheel into a combustion chamber designed with a stiff grate. Such a fully automatic feeding system allows the smaller fuel particles to be combusted during the flight to the grate while more coarse fuel particles are burned on the grate. The system also has the advantage that the fuel is fed gently on the fire, thus reducing airborne emissions of particulate matter.

The primary air is blown with an automatic ventilator through holes in the grate into the glowing fire. The preheated secondary air is blown into the combustion chamber on the top of the burning fuel. The air feeding system adjusts itself automatically according to information from a sensor fixed in the flue gas outlet, minimizing unburned flue gas components and thus meeting the given emission limits. Such devices are characterized by relatively low emissions and the ash can be used as a fertilizer or put on a landfill site depending on the legal frame conditions.

The heat is extracted from the flue gas via a heat exchanger located on top of the combustion device. Within the heat exchanger, the flue gas is cooled down and water is heated up – depending on the heat utilization system – either close to the boiling point (to be used in hot water systems) or to steam, for example, for electricity generation.

Such combustion systems are characterized by a fully automatic operation. They are available on the market in the range of thermal capacities of 300 KW up to approximately 3,500 kW and can be used either for the heat provision for single- or multi-family houses or for industrial process heat. Also, a CHP operation is basically possible for such systems in the upper capacity range if an ORC (Organic Rankine cycle) process is integrated; but the electrical efficiency of such CHP-units are relatively low.

Pyrolysis

In this technical conversion process, solid biofuels are heated up within a nearly oxygen-free environment

(i.e., no oxygen from outside is added, but within the biomass some oxygen is present that might influence the conversion process). At temperatures up to about 200°C, the biomass is first dried and water is evaporated. With increasing temperatures up to roughly 500°C, the organic matter is almost decomposed (i.e., the macromolecules originally within the biomass are split into smaller molecules). During this decomposition process, solid, liquid, and gaseous products are provided from the solid biomass. The share and composition of the different products or product groups depends, for example, on the temperature range the pyrolytic decomposition is realized at, the presence of catalysts, the heating up rate of the biomass, the speed of cooling down the provided products, and the composition of the used solid biofuels. At the moment, two main applications of such a pyrolytic decomposition can be found on the market: processes designed for the production of charcoal and for the provision of bio-oil.

Charcoal from wood or from herbaceous biomass can be produced with a broad variety of different technologies. In developing countries, for example, basic traditional charcoal kilns are usually made from earth or brick, although low-end metal kilns are sometimes found. The overall conversion efficiency between the energy content of the wood and the energy content of the charcoal of such basic devices is rather low (sometimes less than 25%) in general and the airborne emissions of, for example, volatile organic compounds and odorous substances are relatively high. Additionally, considerable amounts of a mixture of toxic liquids (like alcohols and tars) are produced depending on the conversion technology and their operation management.

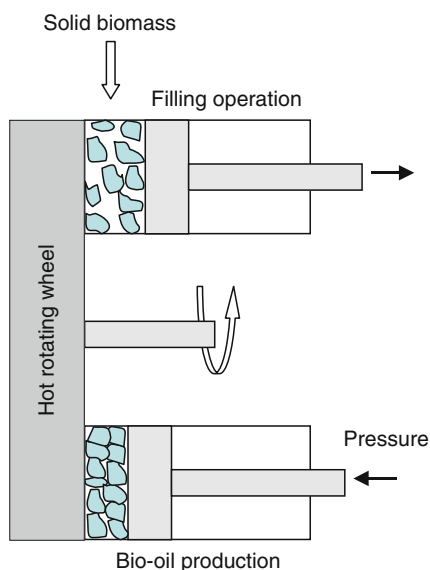
In industrialized countries, charcoal is produced in large, fully automatic industrial devices. In general, a differentiation is made between retort and flush gas processes.

- Within the retort processes the charcoal is produced in a batch mode within a closed container (i.e., retort). Here, the conversion from wood or other solid organic matter to charcoal takes place. The thermal energy necessary to run this process is obtained from the combustion of the gaseous and even liquid products released from the biomass feedstock during this charcoal production. If there is a market the liquid products might be sold.
- Within continuous charcoal production systems (like flush gas processes), the wood (or other solid biomass) is moving continuously through a reactor. This reactor is characterized by different zones with various settings of reaction conditions (e.g., temperature) to ensure that the charcoal is produced continuously and efficiently during the migration of the biogenic material through the reactor. Here, too, the gases and maybe even liquids produced as by-products are used as a source of energy to keep the coalification process going. Depending on the market conditions, the liquid by-products can be sold, for example, to the chemical industry.

With basically similar processes – but different process conditions – the solid biomass can be converted to maximize the yield of liquid products (i.e., bio-oil); the process conditions where the pyrolysis takes place are set to ensure that the main products of the thermochemical conversion process is liquid rather than solid or even gaseous. Due to extensive research activities carried out during the last decades, a broad variety of different technologies are available in various technical development stages attempting to provide pyrolysis oil (i.e., bio-oil), which can easily be used as an liquid energy carrier to be used, for example, in diesel engines. Besides the use as a liquid fuel, bio-oils are also used as a raw material, for example, as a flavor substance for meat products.

With current knowledge, such a conversion of solid organic matter to a liquid can most promisingly be realized with so-called flash pyrolysis. Here the biomass particles are heated up very rapidly (more than 1,000°C/s) and remain in the hot zone for a very short retention time (in general less than 1 s). After this very short time period, the volatile compounds produced by decomposing the organic macromolecules of the solid biomass (i.e., lignin, celluloses) and released from the organic matter are removed quickly from the hot reaction zone. Then they are cooled down rapidly to avoid a further decomposition into gases. To date, various technological approaches for such flash pyrolysis reactors have reached laboratory and pilot stage development level. The first semi-commercial plants are even available. There is also a commercially viable niche application with a very similar technology producing flavor substances.

One example for the technical realization of this principle is a reactor with ablative impact design. Here,



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 6

Pyrolysis system based on a hot rotating wheel [1]

the organic raw material is decomposed into liquid and gaseous components on the surface of a hot rotating wheel (Fig. 6). To avoid further decomposition of the components released from the solid biomass, these products are removed immediately from the hot zone. After that they are quickly cooled down to produce the desired liquid energy carrier. Gaseous and solid components are also produced, which are used to heat the wheel and/or to provide additional products (e.g., charcoal).

The produced pyrolysis oil is a mixture of different hydrocarbons (many of which are partly oxygenated and some of which might be toxic) along with solid carbon (i.e., charcoal particles), ash particles, and water. The actual composition strongly depends among other influencing parameters on the pyrolysis process as well as the specific process conditions, the availability of catalysts, and/or the type of biomass. This is especially true for the composition and structure of the produced hydrocarbons (e.g., chain length, degree of double bonding). This bio-oil is in most cases not stable in air because the double bounds are oxidized. The average heating value of pyrolysis oil is approximately 40% that of petroleum-based fuels. Also, the conversion efficiency between the energy content of

the solid biomass and the produced bio-oil of the fast pyrolysis processes available so far is relatively low.

The overall development goal of such processes is the provision of a liquid energy carrier that can be used directly in engines, for example, for the provision of heat and electricity (CHP) and/or within the transportation sector. Thus far, the pyrolysis oil produced in the available plants cannot be used directly in existing engines. Therefore, the produced oil needs to be upgraded within an expensive process. For example, charcoal and ash particles have to be removed to ensure a clean fuel, and, to increase stability, double bonds need to be broken by adding hydrogen. Additionally, other measures have to be taken to ensure that the viscosity and combustion behavior required by the respective engine is fulfilled. This upgrading process lowers the overall efficiency even further and makes the overall process even more expensive.

Gasification

Gasification describes the conversion of solid biomass at high temperatures into a gaseous fuel. The main objective of this thermochemical conversion is to transfer the maximum possible share of the chemical energy within the biogenic feedstock into a gas useable, for example, as a source of energy. To realize this for physical and chemical reasons, small amounts of oxidizing agents need to be added to this process; this is the difference with pyrolysis, where basically no additional oxygen is added to the conversion process.

This so-called “producer gas” can be used, on one hand, as a fuel for the provision of heat through direct combustion or for the provision of heat and electricity (CHP) in engines, turbines, or even fuel cells. On the other hand, the producer gas can act as a feedstock for the production of liquid and/or gaseous biofuels (like Fischer-Tropsch diesel, biomethane, methanol, hydrogen) as well as for the provision of bulk chemicals and other raw materials.

Biomass gasification consists of the following, more or less spatially distributed, conversion steps: heating and drying, pyrolytic decomposition (i.e., extracting the volatile components by heat), and gasification (i.e., partial oxidation of the products of the pyrolytic decomposition, partial reduction of the oxidation products [CO_2 and H_2O to CO and H_2], and

simultaneous transformation of solid carbon [i.e., charcoal] to CO).

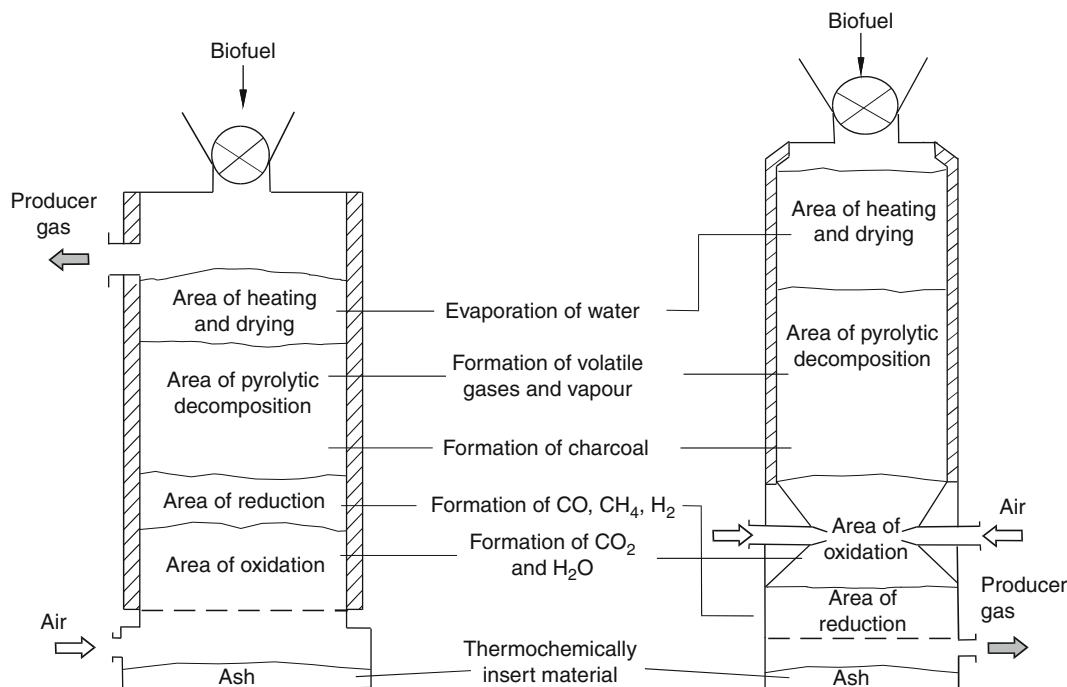
This conversion of solid biomass into an energy rich gas is carried out within a broad variety of different technical concepts developed during the last decades. Each of them offers certain advantages and disadvantages concerning, for example, required feedstock characteristics, installed thermal capacity, technical efforts, and gas quality.

These gasification techniques can be subdivided related to different criteria such as, for example, reactor type (fixed bed or fluidized bed), gasifying agent (air, oxygen, or steam), heat supply into the reactor (directly or indirectly heated) and reactor pressure (atmospheric or pressurized). Here a distinction is made according to the reactor type.

- In fixed-bed reactors (Fig. 7), the feedstock is exposed to the gasifying agent in a packed bed that slowly moves from the top of the gasifier to the bottom, where the ash is discharged. Fixed-bed gasifiers are dense-phase gasifiers. They are characterized by a relatively large amount of fuel exposed

to a limited amount of reactive gas. In fixed-bed reactors, the solid feedstock occupies most of the reactor volume. Depending on the way of the gas flow through the reactor relative to the fuel flow, two types of fixed-bed gasifiers are distinguished: the updraft and the downdraft type. The former is characterized by a relatively cold producer gas with a high amount of condensables (i.e., tars) compared to the latter (i.e., hot producer gas, low tar content). Fixed-bed reactors are used mostly only for small-scale applications.

- Fluidized-bed gasification reactors are lean-phase gasifiers having a low ratio of solids to reactor volume. Typically, the solid feedstock is occupying only a small fraction of the total reactor volume. Such fluidized-bed gasifiers are classified, depending on the intensity of fluidization, as bubbling fluidized-bed gasifiers, or circulating fluidized-bed gasifiers. Basically, fluidized bed gasifiers are a large-scale technology. So far, they are used for CHP applications. In the years to come, the provision of a producer gas to be used for the synthesis of liquid or gaseous biofuels might gain more importance.



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 7

Principle of an updraft gasifier (left) and a downdraft gasifier (right) [1]

Thus, this option is often seen as a key technology also for such applications.

- Within entrained flow gasifier the gasification of the biomass particles takes place within a few seconds during pneumatic transport through the reactor. This requires very small biomass particle diameters and high temperatures to complete the gasification reactions within this short time. The fuel is typically feed in from the top together with the gasification agent (steam/oxygen). In the upper part of the reactor gasification is carried out and in the lower part the producer gas is quenched and separated from the ash. The latter is withdrawn in granulated form. Producer gas leaves the reactor at the lower part.
- Gasifiers have also been developed that cannot easily be classified as belonging to one of the former groups but might have features of both.

Commonly, the overall goal of such a thermochemical gasification is not to provide the gaseous fuel itself but to provide an easy-to-handle and environmentally sound intermediate energy carrier with clearly defined fuel characteristics that can be converted easily into another, more valuable, energy carrier (e.g., electricity, biomethane). Alternatively or additively, the producer gas can also be used as a feedstock for the production of raw materials (e.g., bioplastics, lubricants, bulk chemicals, pharmaceuticals). To reach that goal, an extensive cleaning of the producer gas to fulfill clearly predefined threshold values and even a conditioning is usually necessary to ensure a long lifetime of the downstream conversion with its respective processing device. The reason for this is that the gas produced within the gasifier does usually not match the fuel requirements in terms of condensable organic compounds and/or particles. Additionally, the producer gas might contain some trace elements (like sulfur) that could poison the catalysts used during the downstream processing. If this is the case, additional expensive gas cleaning steps are necessary.

For the provision of a gas to be used as a fuel, for example, for CHP-systems (e.g., engines, turbines) a raw gas cleaning operation – either low temperature wet gas cleaning or, alternatively, hot gas cleaning – can be applied. The technical maturity and effectiveness of wet gas cleaning (e.g., cyclone and filter, scrubbing based on chemical and/or physical absorption) has been well proven for large-scale coal gasification

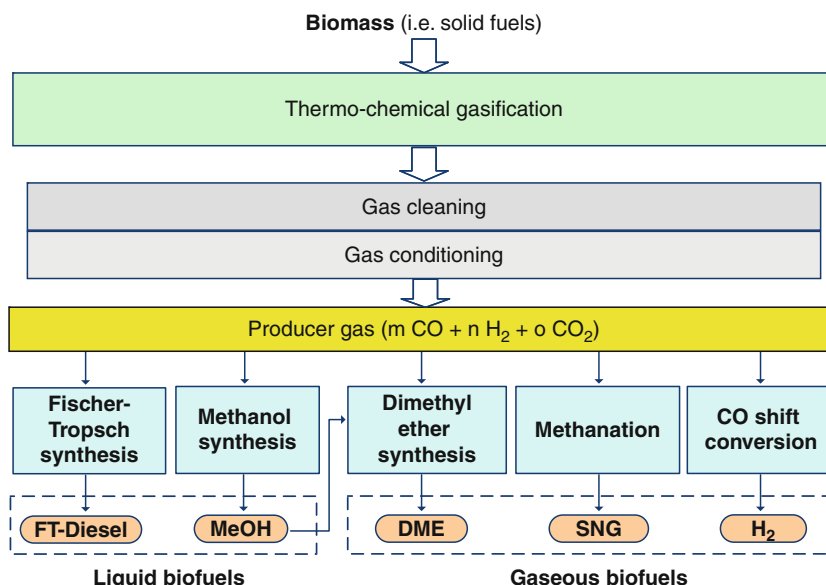
systems. However, not all elements of hot gas cleaning (e.g., tar cracking, granular beds and filters, physical adsorption or chemical absorption, physical absorption) are market mature. Nevertheless, hot gas cleaning offers benefits for the overall energy balance and avoids the production of contaminated waste.

The cleaned producer gas can be used for the provision of electricity within engines or gas turbines. The former has been demonstrated already for years within the gasification plant in Güssing/Austria, where wood chips are gasified and the producer gas is then used within an engine-based CHP-plant for the simultaneous provision of heat and electricity. Similar systems are in operation and under construction or planning in other countries. The next development step will be biomass-based integrated gasification combined cycles (IGCC). Such plants allow providing a significantly higher share of (valuable) electricity and a smaller share of heat. But the technical realization is still quite challenging.

According to the ongoing discussion in energy industry and energy politics, biomass gasification is currently more in discussion as the key process step for the production of synthesized biofuels (Fig. 8) (so-called biofuels of the next generation). Such a synthesis of a secondary energy carrier based on carbon monoxide and hydrogen consists mostly of catalytic induced chemical synthesis processes. And these catalysts used for the realization of such chemical processes are sensitive with respect to some trace elements (e.g., sulfur). If such trace elements are present within the process, the catalyst could be poisoned on the shorter or longer term. This lowers the technical lifetime significantly and makes the process much more expensive. For this reason the producer gas has to be characterized – depending on the demand defined by the involved catalyst – by very low content of impurities that are potentially harmful to the downstream processing steps.

For the provision of a synthesis gas basically the same gas cleaning processes and technologies are used as for gas cleaning for the provision a producer gas, for example, for electricity provision. But due to the much more demanding requests and demands on the quality of the producer gas (e.g., the amount of unwanted impurities) these cleaning technologies are used more intensively within combined processes.

In addition to extensive gas cleaning, the ratio between carbon or carbon monoxide and hydrogen,



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 8

Possibilities to produce liquid and/or gaseous fuels from producer gas respectively from biomass

for example, within the cleaned producer gas and the desired product (i.e., DME, SNG) has to be adjusted (i.e., the producer gas has to be conditioned). For example, the C to H ratio within the solid biofuel (e.g., wood, straw) is in most cases significantly lower compared to this ratio in methane or Fischer-Tropsch diesel. This makes it necessary in most cases to add hydrogen to the overall process (or to remove carbon, which is the less promising option).

Such a necessary adjustment of the gas quality can be realized, for example, by a steam reforming step. Additionally or even alternatively, the gasification can be realized with a gasifying agent rich in hydrogen (e.g., water) instead of air or oxygen to add hydrogen already at this early stage to the overall process.

The cleaned and conditioned gas can then be used for the synthesis of liquid and/or gaseous fuels. Currently, the following four conversion routes for the provision of a liquid or gaseous fuel for transportation purpose are under investigation and partly under development.

- Fischer-Tropsch Synthesis:

$$\text{CO} + 2 \text{H}_2 \rightarrow (-\text{CH}_2-)_{\text{n}} + \text{H}_2\text{O}$$
- Methanol Synthesis:

$$5 \text{H}_2 + \text{CO} + \text{CO}_2 \rightarrow 2 \text{CH}_3\text{OH} + \text{H}_2\text{O}$$

- Dimethylether (DME) Synthesis:

$$3 \text{CO} + 3 \text{H}_2 \rightarrow \text{CH}_3\text{OCH}_3 + \text{CO}_2; \text{CO} + \text{CO}_2 + 5 \text{H}_2 \rightarrow \text{CH}_3\text{OCH}_3 + 2 \text{H}_2\text{O}$$
- Methanation:

$$\text{CO} + 3 \text{H}_2 \rightarrow \text{CH}_4 + \text{H}_2\text{O}; \text{CO}_2 + 4 \text{H}_2 \rightarrow \text{CH}_4 + 2 \text{H}_2\text{O}$$

The synthesis of Fischer-Tropsch diesel, methanol, and methane is market mature and in large-scale operation for decades using fossil fuels (e.g., coal). For biomass feedstock, however, this technology is still under development. So far, none of these synthesis processes are realized on a commercial basis. But due to the successful demonstration of the technological maturity for fossil fuel energy, it can be expected that these processes can also be realized successfully for biomass feedstock.

Physicochemical Conversion

Some biomass components contain fatty and/or oily components (e.g., rape and sunflower seeds, coconuts, peanuts, corn, palm fruits). The content of the vegetable oil or fat within the biomass varies quite significantly. In some cases, the oil seed may contain 40–45% vegetable oil; in other cases the oil content is only within the one digit percent range.

Based on physicochemical processes, the vegetable oil or fat can be removed from the organic material in its pure form and can then be used as a source of energy. Compared to solid biofuels, vegetable oil or fat has some outstanding advantages. It is easy to store, has a high energy content, can easily be handled, and can be used as an energy carrier, for example, in existing oil burner for the provision of heat and/or in some (older) engines for the provision of heat and electricity (CHP). However, just like crude oil, pure vegetable oil cannot always be used easily in its raw or unprocessed form because the fuel characteristics do not necessarily match the fuel standards the conversion device (e.g., engine) is designed for. Thus, this organic material needs to be additionally processed to fulfill the fuel standards valid for the specific application aimed for. Such a processing of the crude vegetable oil or fat can be realized within a crude oil refinery together with crude oil to yield kerosene or diesel fuel (i.e., co-refination). Alternatively, vegetable fats and oils can be hydrogenated and/or chemically treated to meet the fuel characteristics of conventional diesel fuel.

Next, the process technology for the provision of vegetable oil or fats from oil seeds and the provision of a fuel meeting current fuel standards are described.

Oil Production

Depending on the vegetable oil content, the oil characteristic, and the properties of the oil seed, different technical approaches have been developed throughout recent centuries to produce the oil or fat in a cost-effective way. Basically, these approaches consist of one or a combination of the two technical processes, pressing and extraction.

During pressing, the “classical” process for vegetable oil production used by humans since ancient time, the oil is squeezed out of the oil seeds (and therewith out of the organic material) based on a one- or two-stage pressing process. To achieve a maximum oil yield, the organic matter is preheated to lower the viscosity of the oil. Two products are obtained as a result of such a treatment: the liquid vegetable oil and the solid oil cake. The latter still contains 4–10% oil. Sometimes this oil cake is used as cattle feed where the remaining oil contributes to the nutrition value of this product. Even

today such processes are still in large-scale operation (e.g., traditional olive oil production).

Alternatively and/or additionally, the vegetable oil can be removed from the organic material by means of extraction. Such an extraction is realized with the help of a solvent (e.g., hexane) applied in a countermovement to the biomass containing the oil. This technology has been widely employed and optimized for many decades worldwide. It is used on a large scale with in all existing large industrial oil mills. Within such a technical process, two different material streams are produced: the solvent saturated with vegetable oil and the oil-free extraction residue saturated with solvent. Therefore, the solvent must be removed from both material streams. This is usually realized by introducing heat. The solvent is evaporated and leaves the material as vapor. The solvent vapor is collected, condensed, stored, and reused. Compared to pressing, a much higher share of the oil originally contained within the biomass (e.g., oil seed) can be removed. After extraction the meal contains significantly less than 1% oil. In most cases, this basically oil-free residue is used as cattle feed. Alternatively, this biomass can also be used as a substrate for biogas plants or as a fertilizer.

For oil seeds with high oil content, like rape seed, pressing followed by extraction will allow minimizing the costs by maximized oil yields and minimized losses. But also from a technological point of view the combination is more promising for such types of biomass. Therefore, the decisions about using pressing or extraction is mainly determined by economic constraints.

The produced vegetable oil contains about 0.5–6% oil-free solid residues originating from the seed. The amount of such solids within the oil mainly depends on the condition of the pressing aggregate, the realized flow-rate, the kind and status of pressed seed, and the water content in the oil seeds. These solid impurities have to be separated from the vegetable oil by filtration and/or sedimentation to prevent possible problems during the further downstream processing of the vegetable oil. But even after this cleaning step, the vegetable oil is not qualified for direct utilization as an energy carrier because in most cases it still contains unwanted substances (fatty acids, ketones, waxes, pigments, heavy metals, pesticides), reducing shelf life and complicating subsequent processing and use. For this reason, a further refining is needed. This leads typically to a loss of 4–8% of the usable

vegetable oil mass through de-acidification, de-coloring, and steaming. These processes are also needed for the production of vegetable oil as food and fodder as well as for the provision of oil as a raw material (e.g., for the production of cosmetics or chemicals).

Pure vegetable oil can be used in some (mostly older) existing engines, either for mobile (e.g., in cars or especially trucks) or stationary applications (i.e., in engine-based CHP systems). In most cases, vegetable oil in its natural form lowers engine lifetime and increases maintenance requirements because the standards for fossil fuels (like diesel) are only partly fulfilled by crude vegetable oil. Therefore, only under very specific frame conditions the use of crude vegetable oil is a promising option for the transportation sector or to provide power (or power and heat (CHP), if required). Only for heat provision crude vegetable oil can be used in most cases. But due to economic constraints, these applications are only very scarce.

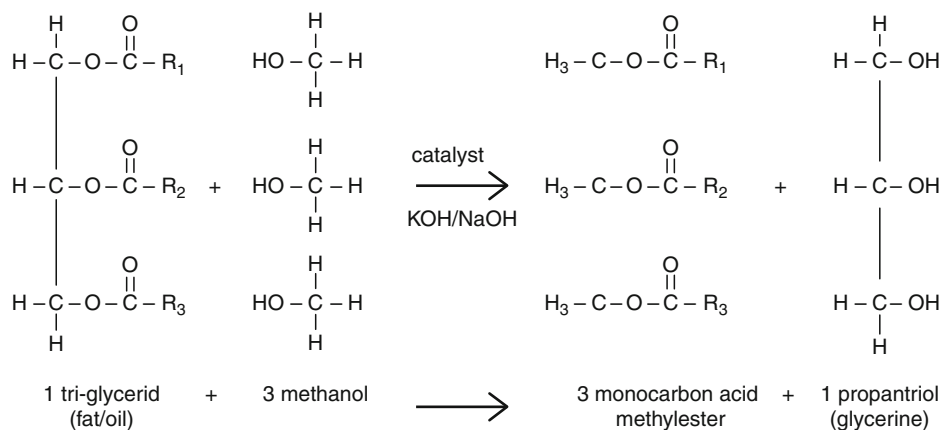
Conversion to a Standardized Fuel

Due to problems with the use of crude vegetable oil in existing diesel engines outlined above, in most cases the oil is converted into a liquid fuel fulfilling characteristic parameters defined within valid fuels standards. Different approaches are possible and realized on the market to achieve this goal.

The most widely realized option to convert refined vegetable oil into a standardized fuel is the conversion

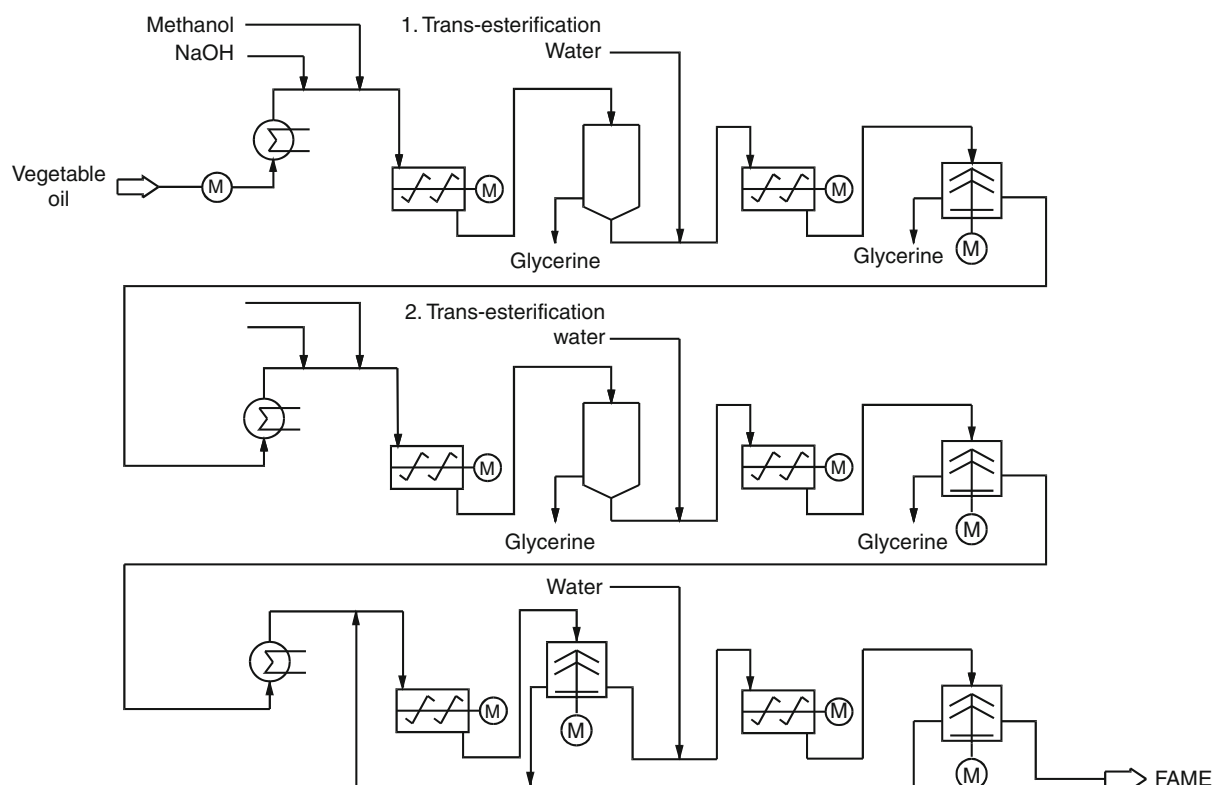
of the oil into fatty acid methyl ester (FAME) (Fig. 9). During this process the glycerin is removed from the triglyceride, which is the common chemical structure of vegetable oil (Fig. 9). To saturate the ester bindings instead of the glycerin, methanol or even ethanol is added to the remnant. This reaction is realized at a certain temperature level and triggered by a catalyst.

This transesterification process can be transformed in various ways into process technology. One example for the technological realization is shown in Fig. 10. According to this, a mixture of vegetable oil together with a catalyst and methanol in surplus (to force the reaction into the right direction) is pumped with a low velocity through a vertical pipe. The low-flow velocity of the liquid ensures that the glycerin produced during the transesterification process taking place can settle down within the reactor and can then be removed from the process. The glycerin can then be cleaned and used as a raw material (e.g., within the pharmaceutical industry) or as a source of energy (e.g., as an additional feedstock for biogas plants). After the removal of the methanol not used during the transesterification process from the remaining mixture, the liquid is cleaned by a multi-stage washing process to fulfill the standardized fuel characteristics. The produced FAME now shows characterizing parameters close to those of conventional diesel fuel. This can be used as a fuel either within most of the existing diesel-driven power trains for cars and trucks or in engine-based CHP-systems without any further problems. Additionally, a mixture



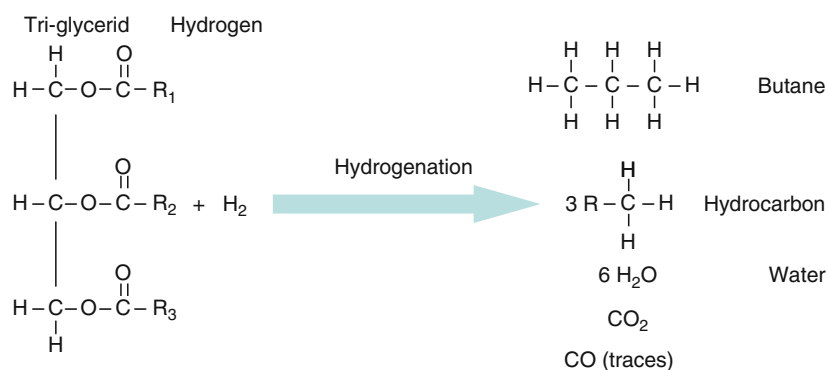
Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 9

Transesterification of vegetable oil to fatty acid methyl ester [1]



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 10

Example for a continuously working transesterification process for FAME manufacturing [1]



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 11

Hydrogenation of vegetable oil [2]

between 0% and 100% with conventional fossil diesel is easily possible. This makes the logistics much easier.

Alternatively to the conversion into FAME, vegetable oil can be treated with hydrogen under presence of a catalyst using the hydrotreating technology usually

employed in conventional crude oil refineries. The product is called hydrogenated vegetable oil (HVO). By doing this the partly existing double bonds of the vegetable oil are saturated with hydrogen and only fully saturated hydrocarbons remain (Fig. 11). Additionally,

the oxygen that is naturally part of the crude vegetable oil molecule is removed from the oil and converted into water. This produced water can then be easily removed from the process. Also, the glycerin linking the three hydrocarbon chains within the oil molecule (i.e., triglyceride) is hydrogenated. During this process (bio-) butane is produced. Thus, fully saturated hydrocarbons (i.e., alkane chains), water and butane are produced. All of these chemicals are desirable within such a hydrogenation process. Not desired (but unavoidable) is the production of carbon dioxide or even carbon monoxide. The former might cause problems within the process technology and the latter could poison the catalyst needed within the process. Therefore, based on technical measures, such a production has to be avoided as much as possible.

Such a hydrogenation is realized within a hydro-treater, which is also a part of a conventional crude oil refinery. Within such a reactor, the chemical reactions mentioned above take place. They are supported by catalysts to ensure that hydrocarbon chains are produced that fulfill the given fuel specifications. This production pathway is market mature and it can be expected that it will be used more widely in the years to come.

Basically the same process can also be realized within a conventional crude oil refinery. Here, the crude vegetable oil and the crude fossil oil can be treated together (so-called co-refining). The vegetable oil is mixed with the crude oil fraction coming from the atmospheric distillation before it is pumped into

the hydrofiner. Within the hydrofiner, the hydrogenation of the vegetable oil is realized. In parallel, the sulfur originating from the crude fossil oil is converted into H_2S , which is the main task of this system element within a conventional refinery to fulfill the ambitious sulfur limits set by the government in recent years within the refinery products. The gaseous H_2S can then easily be removed from the liquids and converted within a Claus process into elementary sulfur. It has been shown that co-processing of vegetable oil with the diesel or kerosene crude oil fraction within a hydrofiner usually available in existing crude oil refineries can be realized successfully without major technical problems.

Basically, all three ways to treat vegetable oil are technically feasible and allow the production of a fuel fulfilling the existing diesel standards.

Use

FAME, HVO, or co-processed vegetable oil can be used directly as a substitute for diesel fuel in conventional compression ignition engines or in CHP-systems with installed capacities from some tens of kW up to several tens of MW. Prerequisite for that is that the treated vegetable oil fulfils the existing standards (Table 3). Normally, this is easily possible with co-refined vegetable oil and HVO. But also with FAME based on rape oil this is usually the case. It might be difficult, however, using other types of vegetable oil for the production of FAME (like palm oil).

Biomass as Renewable Source of Energy, Possible Conversion Routes. Table 3 Selected properties of diesel fuel, FAME and rape oil (various sources)

	Diesel fuel/light heating oil	FAME	Rape oil
Density (15°C) in kg/m ³	820–845	875–900	900–930
Viscosity (40°C) in mm ² /s	2.0–8.0	3.08	78.7
Flash point in °C	>55	130	Min. 220
CFPP-value in °C (summer/winter)	Max. 0 Max. –20	Max. 0 Max. –20	
Sulfur content in mg/kg	Max. 350	Max. 100	Max. 20
Cetan-value	Min. 51	55	
Calorific value in MJ/kg	42.7	37.9	Min. 35

Biochemical Conversion

All existing organic matter can be decomposed naturally through biological processes. But some of these biological degradation processes can be harnessed to produce fuels useable in technical processes.

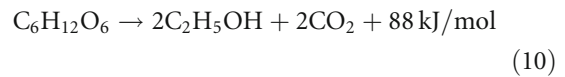
- Composting occurs if oxygen is available. During this aerobic biological process biomass is degraded by bacteria mainly to carbon dioxide (CO₂) and water (H₂O) while releasing low-temperature heat. This thermal energy can, in principle, be used via a heat pump for heat provision. But, for the time being, this option is only of theoretical importance. Nevertheless large volumes of biomass are composted and the released thermal energy is wasted.
- Under anaerobic (oxygen free) or nearly anaerobic conditions, a huge variety of partly very different degrading processes are employed by microorganisms. Only very few of them are deeply understood and used by humans so far. Currently, most relevant to energy are ethanol production via alcoholic fermentation and biogas (methane) production via anaerobic digestion. Nevertheless other biochemical conversion processes under anaerobic conditions for the provision of energy carrier and chemicals are under investigation and/or development.

Alcoholic Fermentation

Under anaerobic conditions, sugar (C₆H₁₂O₆) can be converted to ethanol (C₂H₅OH), carbon dioxide (CO₂), and low temperature heat by yeast (and thus by biological processes). Because starch and even celluloses can be transformed more or less easily into sugar, biomass fractions containing these components are also a potential resource for the production of ethanol in addition to naturally sugar-containing crops like sugar cane and sugar beet. For fuel, ethanol is needed in its pure form and therefore further processing and upgrading steps are needed after fermentation has taken place.

Basics Sugar (C₆H₁₂O₆) is converted to ethanol (C₂H₅OH), carbon dioxide (CO₂), and low-

temperature heat by yeast under anaerobic conditions according to Eq. 10.



According to this equation, 100 kg of sugar is converted into 51.14 kg of ethanol and 48.86 kg of carbon dioxide and 400 kJ of heat. This thermal energy is needed to support the growth of the microorganisms realizing the bio-chemical conversion. To reach a quick and complete transformation of the available sugar into ethanol, additional growth supporter and mineral nutrients, as well as an optimal environment (i.e., temperature level, pH-value) are needed. Most bioethanol processes are realized at a temperature level between 25°C and 40°C. This process and the influencing parameters are well known because of humanity's long and extensive production of alcoholic beverages.

Because starch and even celluloses can be converted into sugar, such biomass fractions are also a potential resource for the production of ethanol in addition to naturally sugar-containing crops.

Substrate Production For fermentation, sugar needs to be available in a water solution. The technological processes to provide such a sugar solution depend on the used feedstock.

- *Biomass containing sugar.* Typically sugar is produced from sugar cane and sugar beet.
 - Sugar cane is a grass growing mainly under tropical conditions containing a sweet liquid that can easily be removed by pressing from the organic matter. It accounts for about 30% of the weight of fresh cane. The fiber remaining after pressing (bagasse) is often used as a solid biofuel for the provision of the energy needed to run a sugar mill and/or an alcohol production factory. After several preparation and processing steps this liquid can be used as a feedstock for alcoholic fermentation.
 - Sugar beet, which grows in temperate climates, is first chipped into small pieces from which the sugar is extracted by means of water applied in countercurrent to the flow direction of the chips. The remaining products are the nearly sugar-free extracted beet chips, which can

be used, for example, as a cattle feed or a substrate for biogas plants and the water with the sugar. After several cleaning steps this mixture of water and sugar can be used for the alcoholic fermentation.

- **Biomass containing starch.** Beside other chemical substances cereal, corn, potatoes, topinambur, maniok, and other similar crops contain also starch. Starch is a polysaccharide consisting of long chains of different glucose molecules. To produce sugar from starch, this polysaccharide has to be decomposed in single saccharide rings by means of, for example, biological processes based on enzymes. Due to the broad variety of starch-containing biomass crops, no typical conversion process is available on the market. Therefore, for each raw material used so far, a conversion process has been developed and optimized in the past. In most cases, however, water is added to the chipped or milled organic material. The consequence is a swelling of the mixture because the water is attached to the starch. Due to this process the starch becomes a paste. To this paste the respective enzyme adapted to each type of biomass feedstock is added. Under the right process conditions (e.g., temperature, pH-value), starch is then converted into sugar. And this sugar can then be used as a feedstock for the alcoholic fermentation.
- **Biomass containing celluloses.** Basically, all organic matter contains cellulose as this is one of the most important elements of plant material. This is especially true for lignocellulosic biomass (like wood) that cannot be used for food or fodder (and thus there is no competition between food and fuel). Like starch, cellulose is composed during the plant growth from different sugar components. Therefore, cellulose can be split again into sugar molecules. This can be realized through biological and nonbiological processes. The former are based on special enzymes still under development and optimization. But the conversion rate of such biological conversion routes is still relatively slow and the biocatalysts are comparable expensive; therefore, commercialization has not taken place so far. The latter are realized with an acid-based hydrolysis partly supported by a catalyst and thus in a “classical” chemical way. Such a hydrolysis process

is technologically very demanding and characterized by a low overall efficiency. Therefore, this pathway is not realized on a commercial basis for the time being. To minimize the drawbacks of both options, R&D activities are focusing on a combination of a chemical and a biological conversion. For these reasons so far, alcoholic fermentation based on sugar from celluloses has no market importance, but numerous R&D and market introduction activities are ongoing in this field.

Fermentation For alcoholic fermentation, the sugar and water mixture is inoculated with yeast catalyzing the conversion process. From a technological point of view, this can be accomplished in two different ways. Discontinuous (batch) operation is usually done for small-scale production of high-quality spirits as beverages; continuous operations are used in large-scale systems for production of ethanol as a raw material for the chemical industry as well as for fuel. Within such a continuous operation the temperature as well as the pH-value has to be controlled. Additionally, it might be necessary to add some nutrients to allow a fast and efficient conversion. After fermentation, the yeast is removed from the slurry and recycled.

Production of Pure Alcohol After fermentation has taken place, the resulting material contains only 8–10% alcohol. The rest is primarily water and among others residues from the sugar- or starch-containing organic material. To remove the alcohol from this mixture distillation and/or rectification are done using a crude alcohol column.

Due to physical reasons, the result of such a distillation is an alcohol-water-mixture with a high share of alcohol (more than 80%) and a slurry without significant alcohol content (i.e., stillage). The latter is a by-product and can be used in its dried form as an animal fodder and/or fertilizer. It is also suitable for biogas production. This technology is in large-scale operation worldwide.

For physical reasons, at best, distillation and rectification will only achieve 95–96% pure ethanol because at this concentration water and ethanol forms an azeotropic mixture. A mixture of those two substances cannot be subdivided based on physical processes (like distillation) any more. But bioethanol used as an

engine fuel must be 99.9% pure. For this reason, an additional cleaning step called purification is integrated within the overall process. One (older) possibility for that is to add a third chemical (expedient) to the alcohol-water-mixture producing a mixture of alcohol-chemical plus water-chemical. Afterwards, the chemical is removed from both mixtures and re-used. Another nowadays more widely used possibility is the use of molecular sieves.

Use In engines, ethanol can be used fully or partly as a substitute for gasoline although the lower heating value (LHV) of ethanol is lower compared to that of gasoline (Table 4). The combustion of ethanol, however, requires a lower air volume. Therefore, the heating value of the mixture pressed into the cylinder is more or less the same for ethanol and gasoline. This is the reason why an engine powered by ethanol produces the same power as an engine driven by gasoline.

Nevertheless, internal combustion engines must be specially adapted to the use of pure ethanol, because ethanol shows a different combustion behavior compared to gasoline. Therefore, adaptation kits have been developed for several types of engines and been successfully used in several countries (e.g., in Brazil). Thus pure ethanol is an (expensive) alternative for the

substitution of fossil gasoline under specific frame conditions to be defined by the respective government. One challenge of the use of pure ethanol is that the existing distribution networks need to be adjusted and persistent problems (like water retention during storage) have to be solved. For this reason, in most countries bioethanol is not used in its pure form to avoid these challenges. Therefore, a low share of ethanol is mixed with a high share of gasoline (a maximum of 10% ethanol to gasoline). With such a relatively low fraction of bioethanol within the usually used gasoline, the resulting mixture can be used without any known problems in basically all existing gasoline driven engines and within the available distribution infrastructure. Such a solution is also supported by the fact that ethanol contributes still and will contribute in the foreseeable future only to a minor extent to cover the demand for transportation fuels. Another benefit of such a strategy is that the supply is fully secured even if the availability of bioethanol is interrupted.

Alternatively, ethanol can be converted into ETBE to be used as a pollution-reducing gasoline additive. Bioethanol is also being considered for powering fuel cells in future design and applications.

Anaerobic Digestion

During anaerobic digestion, organic material is decomposed in an oxygen-free atmosphere by bacteria releasing an energy rich gas, called biogas or, depending on where it is produced, landfill gas (LFG) or sewage gas. This gas usually contains slightly more than 50% methane (CH_4), which is the only energy providing component. The rest is carbon dioxide (CO_2) and some impurities of minor importance. Such biologically driven decomposition of biomass occurs in nature, for example, at the bottom of lakes within the oxygen-free parts of sediments containing crushed organic material, and takes place in oxygen-free parts of landfills and dumps where the organic fraction of the waste material is converted into landfill gas.

Basics Degradable organic material and freedom from oxygen, nutrients for the bacteria and absence of harmful, pathologic. and inhibiting substances are needed for a successful biogas production. The organic

Biomass as Renewable Source of Energy, Possible Conversion Routes. Table 4 Selected properties of fuels

	Ethanol	Gasoline
Carbon-share in %	52	86
Hydrogen-share in %	13	14
Oxygen-share in %	35	0
Net calorific value in MJ/kg	26.8	42.7
Net calorific value in MJ/l	21.3	ca. 32.0
Density (15°C) in kg/l	0.794	0.72–0.78
Viscosity (20°C) in mm^2/s	1.5	0.6
Boiling point in °C	78	25 – 215
Flame point in °C	12.8	–42.8
Ignition temperature in °C	420	ca. 300
Evaporation heat in kJ/kg	904	380–500
Minimum air volume in kg/kg	9	14.8
Octane-value	107	93

material should also be easily accessible to bacteria. Therefore, a slurry of biomass with high water content is most promising.

Well-suited for such an anaerobic digestion are material streams where the biomass occurs already within an aqueous solution. Typical examples are agricultural residues (e.g., liquid manure, leaves from sugar beet), residues from the food processing industry (e.g., slurry of fruit and potato processing, some types of slaughterhouse residues), and some other waste streams (e.g., sewage sludge, organic waste fraction from municipalities). Additionally, energy crops like maize silage or silage based on a corn-cob-mix can be used as a substrate. Only biomass containing high shares of lignin like wood cannot be degraded by anaerobic bacteria due to biological reasons.

During the anaerobic digestion process, organic matter is degraded by three different kinds of bacteria: fermentative, acetogenic, and methanogenic. The first two bacteria families degrade the complex organic compounds biomass consists of into simpler intermediates (Fig. 12). These intermediate products are then converted to methane and carbon dioxide by the methanogenic bacteria.

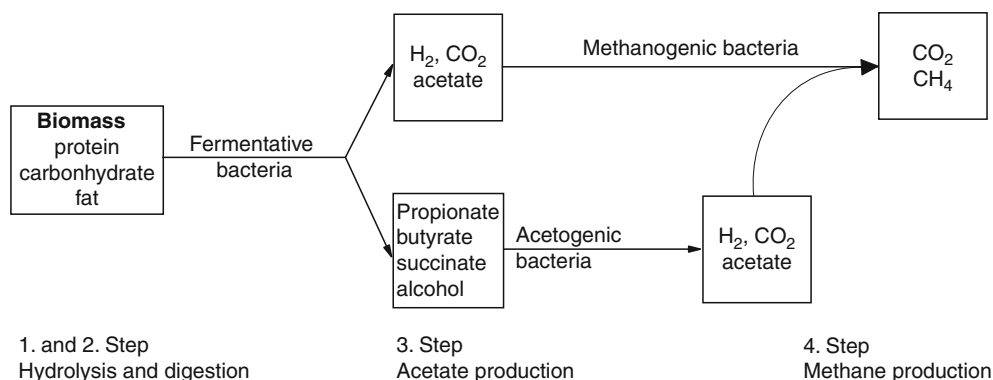
Anaerobic digestion relies on a dynamic equilibrium among the three bacterial groups, which is influenced, for example, by temperature. Most digesters operate in the mesophilic temperature regime, which is characterized by temperatures of around 35°C. Others operate in the thermophilic regime, around 55°C. Up to the temperature of peak microbial activity, which depends on the type of the

involved bacteria groups, higher operating temperatures produce greater metabolic activity within either regime. Additionally to that, the pH-value as well as the composition of the biomass in relation to easily degradable compounds of the organic material affects the performance of the bacteria also. For optimal fermentation, pH-values between 6.8 and 7.2 are often maintained by use of buffers. Additionally, the availability or absence of nutrients and/or trace elements needed for the growth of the bacteria could influence the anaerobic degradation significantly.

The composition of the produced biogas is typically about one half to maximum two thirds methane and one third to one half carbon dioxide. Additionally, the biogas may contain trace substances such as H₂S. The mixture of the biogas depends on the composition of the biomass, the process conditions, and various other parameters. The lower heating value (LHV) of biogas, which depends basically only on the methane content, ranges from 14 to 29 MJ/m³.

Expected biogas yields for different substrates are given in Table 5. Already within the animal stomach digested substrates like animal manure and droppings show in general considerable smaller yields than fresh material (e.g., road side green, sugar beet leaves).

The bacteria mixture realizing the anaerobic decomposition of the organic material use relatively little of the energy contained within the biomass for their own survival; this is one of the reasons why the growth rate of these bacteria is relatively slow. Additionally, they produce only very few (waste) heat; this is why the substrate used within biogas plants have to be



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 12

Anaerobic digestion process scheme [1]

Biomass as Renewable Source of Energy, Possible Conversion Routes. Table 5 Average biogas yields for different substrates (various sources)

Material	Yield of biogas in m ³ /t organic dry matter	Material	Yield of biogas in m ³ /t organic dry matter
Liquid manure from beef	250	Paunch content	420–520
Liquid manure from pork	480	Rey straw	300–350
Droppings from chicken	450	Potato herbs	560
Sewage sludge	400	Sugar beet leaves	550
Organic waste from households	170–220	Food residues	80–120
Waste fat	1,040	Waste water from brewing industries	500
Roadside green	550	Waste water from sugar industries	650

heated. These two facts make this conversion process of organic material into an energy rich gas fairly efficient compared to, for example, the aerobic conversion processes.

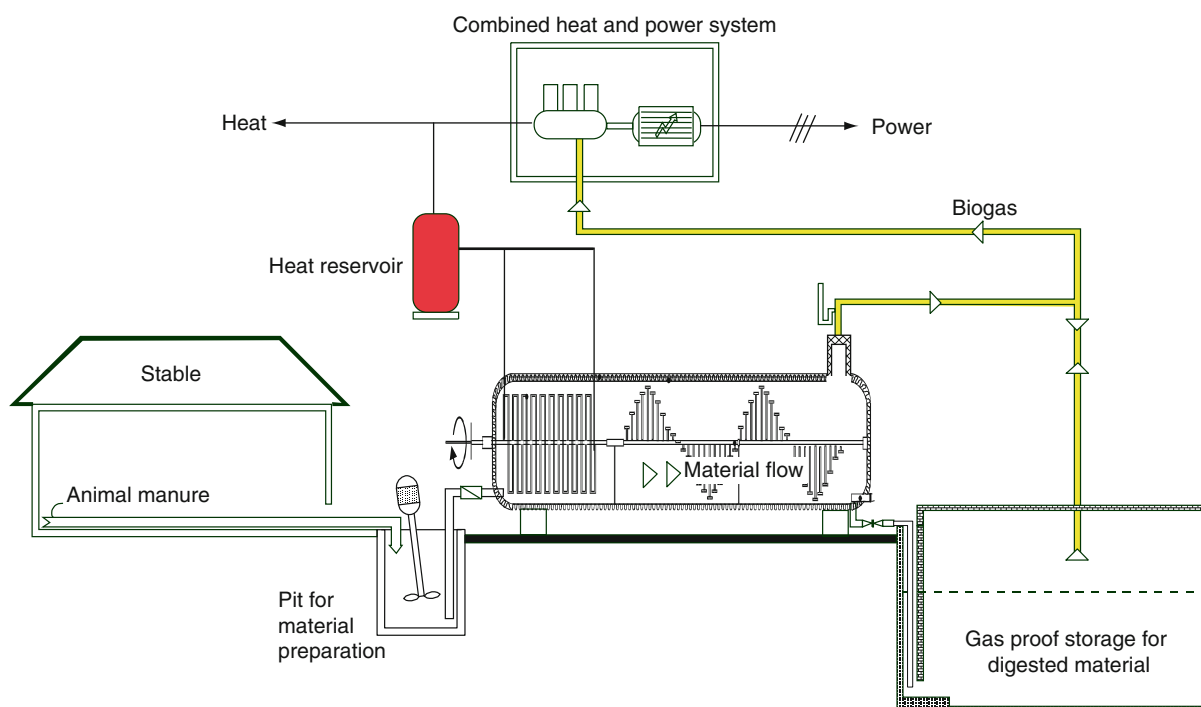
Slurries of organic matter with more than roughly 66% water ensure optimal process conditions with a good access of the bacteria to the organic material. Under these circumstances, the gas yield is maximized. To stabilize and optimize the overall production rates, the slurry should be kept stable at a certain temperature level corresponding to the temperature optimum defined by the used bacterial species. Nevertheless, biogas production will also occur at lower temperatures, but essentially stops below 10°C. But due to very low conversion rates the biogas production on such low temperatures has no importance for

technical processes optimized to maximize the space time yield.

Process Technology The biological degradation process can be transformed into process technology, taking the substrate characteristics as well as the demands of the bacteria into consideration. Due to very different substrates as well as changing bacteria groups a broad variety of different concepts for an optimized biogas production have been developed. And this development is still ongoing with the overall goal to increase the space time yield.

A biogas plant as shown in Fig. 13 is a typical example for a small scale plant using agricultural substrates available within industrialized countries. Within such a plant, preparation of the feedstock is needed that might include short-time storage, sedimentation of mineral contaminants (like sand, stones), crushing the organic material into small pieces (if necessary), mixing of different types of feedstock to maximize the gas yield and to harmonize the substrate composition, and heating to the temperature level the biogas plant operates. After this preparation, the feedstock is pumped into the biogas reactor where the anaerobic fermentation takes place. For successful operation and a maximized gas yield, the bacteria must always be well-mixed with the organic material to be decomposed; therefore, a respective system element is conclusively needed. It is also important to realize a good temperature distribution within the reactor. Within the example shown in Fig. 13, this is realized by a heater that is integrated within the reactor together with the mixer. The biogas is removed from the top of the plant and, after removal of impurities like water and particles, stored before use as a source of energy is realized. Depending on the substrate, sulfur has to be removed from the biogas for environmental reasons and to extend the technical lifetime of the plant (i.e., H₂S forms with water an acid responsible for an increased corrosion). Especially in agricultural biogas plants, this is realized by a biological process where the H₂S occurring within the biogas is reduced to elementary sulfur by specific bacteria groups.

The digested material is removed from the reactor and stored in a tank where a small amount of additional biogas is produced. Therefore, this storage facility should be covered gas tight to avoid the release of



Biomass as Renewable Source of Energy, Possible Conversion Routes. Figure 13

Small scale biogas plant using animal manure as feedstock and commonly used in countries like Denmark, Germany, and Austria [3]

the produced gas into the atmosphere because methane as the most important component within the biogas is harmful to global climate. This digested slurry can be used as a fertilizer, because it contains the nitrogen as well as all the other trace elements originally part of the feedstock and needed to allow plants to grow. Thus, biogas technology could help to close the nutrient cycle. This is of increasing importance for the environmentally sound management of organic material.

Biogas as a Fuel So far biogas is used mainly in a boiler, stove, or engine for the provision of heat, mechanical power, and/or electricity. From a systems point of view, the use within a CHP unit is most promising related to the overall energetic and exergetic efficiency. Part of the heat and electricity produced within such a coupled process is often partly used for heating up the feedstock and running the electrically driven system elements of the plant. Such a system layout is most widely used in industrialized countries.

Alternatively or additionally, biogas can also be feed into the natural gas system. This requires an upgrading

of the biogas to fulfill the gas standards valid for the gas distribution system. Such a feed-in of the biogas upgraded to biomethane is realized in an increasing manner in Switzerland, Germany, and Sweden, for example. Based on that feed-in into the gas grid, the biomethane can be used highly efficient within the heat market (with condensing-boiler technology), the electricity market (with IGCC plants), and/or the transportation market (within CNG vehicles). The use as a transportation fuel seems to be an especially promising option due to the very high hectare-specific conversion efficiency.

Future Directions

Biomass as an energy carrier will continue to be an important source of energy within the global energy system. Political efforts to reduce greenhouse gas emissions will continue to grow in the years to come and thus support the use of biomass as an energy carrier. This development will additionally be supported as prices for fossil fuel energy move upwards and as

awareness grows of the unwanted effects on global climate of the use of fossil fuel energy.

But, the limited biomass resources are also needed to meet the demand for food and fodder as well as for raw material. To meet the growing demand for bioenergy against this background biomass conversion technologies are forced to convert the biomass highly efficient into heat, electricity, and/or power not only due to the resulting economic constraints. The biomass conversion technologies must be technologically reliable, environmentally sound, socially acceptable, and economically feasible. Due to the long history of the energetic biomass use and the successful R&D activities in recent years, especially within the European Union, already today a wide range of conversion technologies fulfilling these criteria are available for the provision of useful energy and/or secondary energy carrier from the various biomass fractions available on the market. These conversion plants are designed mostly to be used in industrialized countries. Nevertheless, the development of further improved systems for industrialized as well as for developing countries will remain on the R&D agenda for academia and industry with highest priority in the years to come. This is especially true due to the fact that heat provision from solid biomass in developing countries (which is globally the biggest single energy market for biomass) is still realized in a very inefficient and environmentally harmful manner.

The foreseeable shortage in biomass available to be used as an energy carrier and the resulting price increase makes it necessary in the future to further optimize the overall provision chain. Improved and new biomass conversion technologies can only be operated with a maximum technical, economic, and environmental benefit if they are embedded within an overall provision chain where the different single processes covering the life cycle from biomass to bioenergy (i.e., from cradle to grave) are interlinked in an optimal way. Therefore, another important task for the years to come is it to develop procedures and tools for the assessment and optimization of overall provision chains. This is especially true for the optimal definition of the interface between different processes composing an overall provision chain.

Besides better conversion systems embedded in improved provision chains, the biomass available for energy purposes must be expanded. Increasing demand

for biomass by a globally fast growing population of humans has to be taken into consideration. Therefore, this goal can only be achieved if better agricultural and forestry management schemes are developed and implemented based on existing and “new” cash crops with significantly higher yields in average. Such measures are probably not sufficient to cover the increasing demand for biomass from the food and fodder markets, and the markets for biomass as a raw material and the energy markets. For this reason, the limited biomass resources must be used more efficiently – and this is true for all markets.

Based on such measures, it can be expected that biomass for energy can contribute increasingly to help meeting some of the global energy demand in a technical feasible, environmentally promising, and economic sound way.

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Biomass Combustion for Electricity Generation

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Article Outline

Glossary
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Glossary

Biomass Includes all kinds of material that were directly or indirectly derived not too long ago from contemporary photosynthesis reactions, such as vegetal matter and its derivatives.

Biogas A mixture of mainly methane and carbon dioxide produced by bacterial degradation of organic matter and used as a fuel.

Biofuel Fuel derived from organic matter (obtained directly from plants, or indirectly from agricultural, commercial, domestic, and/or industrial wastes) instead of from fossil products.

Renewable energy Energy, which is energy generated from natural resources such as sunlight, wind, rain, tides, and geothermal heat, which are renewable (naturally replenished).

Combustion A chemical reaction that occurs between a fuel and an oxidizing agent that produces energy, usually in the form of heat and light.

Gasification Any chemical or heat process used to convert a substance to a gas.

Environment Most commonly used describing “natural” environment and means the sum of all living and nonliving things that surround an organism, or group of organisms.

Electricity generation The process of creating electricity from other forms of energy.

Combined heat and power The use of a heat engine or a power station to simultaneously generate both electricity and useful heat.

Subject Importance and Definition

Biomass contributes worldwide around with more than 10% to the overall primary energy consumption. Whereas the majority of this is the traditional utilization of biomass (firewood) in developing countries, a substantial portion is also used for electricity generation. In 2009, biomass contributed almost 10% to the overall renewable energy electricity generation worldwide [10, 18].

Subject of this article is therefore the description of the state-of-the-art technologies, environmental impacts including greenhouse gas emission balances, as well as financial aspects of using biomass for electricity generation by means of combustion.

Biomass can be converted by various types of technologies to a solid, liquid, and/or gaseous fuel. Solid biomass can be burned in boilers to run, e.g., steam turbines or steam engines. Biogas can be combusted in engines; this is also true for liquid biofuels like biodiesel or bioethanol. The latter two options can of course also be burned in a boiler to produce steam and then electricity. As it can be seen from this, the general term “biomass combustion to electricity generation” includes a very wide spectrum of different technologies.

However, within the modern electricity sector the widest application by far is to burn solid biofuels. With the resulting thermal energy a water-steam cycle is operated to produce electricity through a steam turbine and an electric generator. Therefore the focus of this article is related to this way of energy conversion.

Introduction

Biomass is the oldest way of satisfying the energy demand of humankind. Historically, using firewood was for a long time the only way of satisfying the energy needs of human beings.

When the electricity sector started to develop in the late nineteenth century, the main energy sources used for the conversion into electricity have been for a long time coal and oil. Then in the 1950s and 1960s the

introduction of nuclear energy followed. Nowadays, additionally, natural gas and all types of renewable energies are used for electricity generation. It was only in the last 3 decades, starting with first biomass and biogas plants in the 1970s, that biomass was also regarded as a possible energy source for the grid-connected electricity generation. First applications came along mostly in Western Europe, here mainly in Scandinavia, and in the USA. For example, in the early 1980s about 850 MW of biomass power plant capacity had already been operated grid-connected in California [1].

The term “biomass combustion to electricity generation” is defined broadly and covers a wide spectrum of possible conversion technologies. For this reason, the focus of this paper is put on the combustion of solid biomass and the use of a water-steam cycle. For this so defined subject, this article provides a comprehensive overview of technology, environmental and financial aspects, whereby the major focus is put on technology. Within this part, the article tries to follow the energy conversion path from biomass (and briefly extending this energy chain before the biomass formation to solar energy) to electricity.

Therefore, after a general overview of the energy conversion path from solar energy to electricity (section “[Biomass Chains for Electricity Generation](#)”), the technical description starts with the discussion of the origination of biomass which can be used for combustion together with some key features of biomass (section “[Key Properties of Biomass](#)”). This is followed by the description of the energy conversion pathway from the solid biofuel to the electricity to be feed into the grid (section “[Energy Conversion Technology](#)”). This part starts with an overall presentation of the energy chain from biomass to electricity. After a description of preprocessing, transportation, and storage of biomass, the different conversion steps of biomass are presented – (1) from chemical to thermal energy, (2) from thermal energy to mechanical energy, and (3) from mechanical energy to electrical energy (sections “[Conversion of Chemical into Thermal Energy](#)” to “[Electric Energy Transformation](#)”). Of the various conversion steps, combustion and gasification are explained. Additional plant components are discussed to round up the technical picture given (sections “[Other Plant Components](#)” and “[Ash](#)”).

After analyzing the environmental impacts (section “[Environmental Impacts](#)”), including carbon footprinting and an excursus on biomass co-firing as a very important side-topic within the biomass to electricity subject (section “[Excursus: Co-firing Concepts](#)”) an overview of the actual cost situation is given, together with an example for a financial calculation (section “[Cost Analysis](#)”).

Finally an overview of the actual market status is given followed by a discussion on the future perspectives of biomass in the electricity sector (section “[Future Perspectives](#)”).

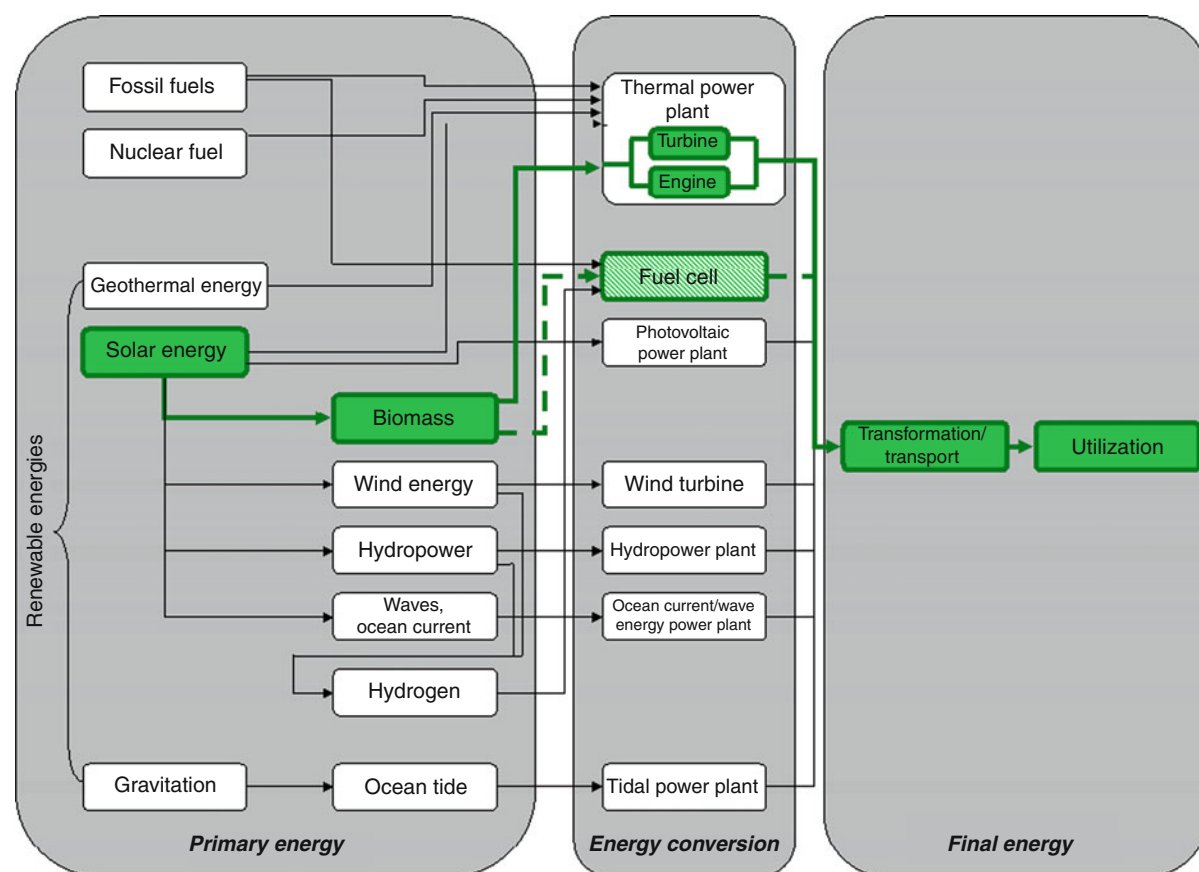
Biomass as Energy Carrier

The energy on earth origins from three different primary energy sources: solar radiation, geothermal heat,

as well as gravitation and motion of planets. Out of this, solar radiation has by far the largest share [16].

From these three natural sources a broad variety of different further energy streams or carriers are resulting on earth. This can be seen in [Fig. 1](#). From all the different energy sources provided indirectly by solar energy (like wind, hydro, wave) biomass is one of these energy carriers representing stored solar energy.

Additionally, [Fig. 1](#) shows in green the principle path of biomass combustion to electricity generation and its utilization, which is the subject of this article. According to this, the conversion pathway under consideration here is from solar energy over biomass to any kind of energy conversion within a thermal power plant, in which, beside boilers and other plant components, the key component is the facility, in which thermal energy is converted into mechanical energy, which



Biomass Combustion for Electricity Generation. Figure 1

Energy sources on earth; solar-biomass-heat-electricity path in green (According to [6], with own adjustments)

can either be a turbine or an engine. Beside this major path, biomass also can be converted into electricity by means of using fuel cells. However, this application is actually only of minor importance due to its high cost and therefore not further analyzed below.

Within a photosynthetic process, solar radiation is converted into organic material. Animal biomass results from this type of biomass via the food chain. Based on this, a definition of biomass can be derived: biomass includes all kinds of materials that were directly or indirectly derived not too long ago from contemporary photosynthetic reactions, such as vegetal matter and its derivatives: wood fuel, wood derived fuel, fuel crops, agricultural and agro-industrial by-products, and animal by-products [12].

The term biomass does not include all materials based on organic molecules (hydrocarbons), e.g., plastics. Additionally most of the definitions, like the above, does not include fossil organic material like peat and (petroleum based) oil.

Biomass therefore includes vegetal and animal mass (plants and animals), the resulting residues (e.g., animal excrements), dead (but not fossil) plant material (e.g., straw) and animal mass, as well as material resulting from technical conversion and/or a material utilization processes (e.g., paper, vegetable oil, alcohol) [6].

Biomass Chains for Electricity Generation

For the conversion of biomass to electricity, a number of processing and energy conversion steps are needed. The variety of the respective process and supply chains for biomass-to-energy and how herein the pathway to electricity is embedded is shown in Fig. 2. When talking about biomass combustion to electricity, usually any kind of solid biomass is used. This is very often true for residues, mostly from plant material to be harvested or collected. Then the biomass is transported from its location of origin either directly to the location of the combustion plant or any kind of pretreatment facility. The biomass is then feed as a solid fuel into the boiler.

Biomass is then converted into heat within the combustion process. Afterward this heat is transferred first into mechanical energy via any kind of

turbine or engine and afterward into electricity via a generator.

An efficient use of biomass through the combustion process usually involves a combination of using electricity and heat in parallel as final energy, thus speaking about combined heat and power plants (CHP).

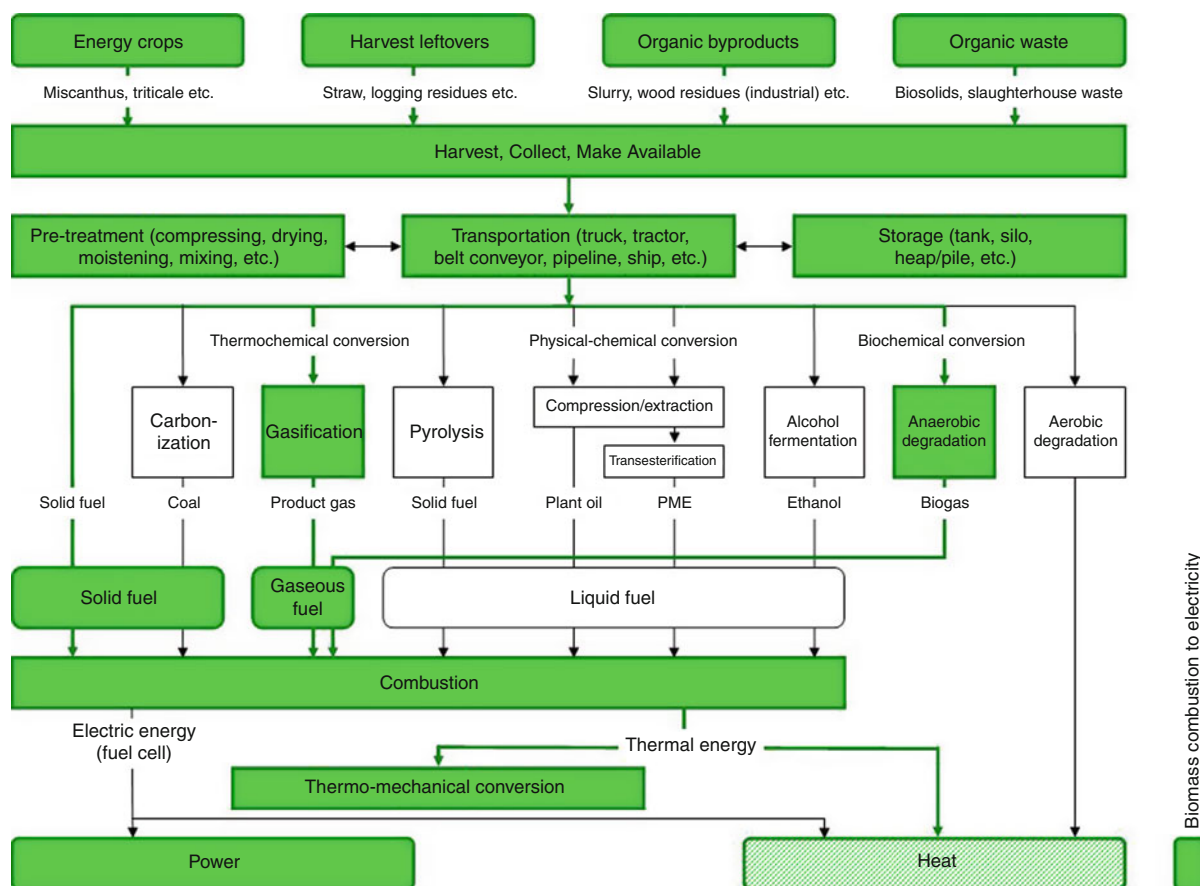
In the following descriptions, the focus is on systems based on combustion as well as on heat and power generation facilities. This facility is in most cases associated with a number of side facilities needed for a proper functioning of the whole plant. Among them are biomass pretreatment facilities and storage facilities.

Key Properties of Biomass

The whole process of biomass utilization to electricity generation is influenced by the physical characteristics as well as the chemical composition of the solid biofuel. Some of these characteristics most important with regard to biomass combustion are discussed below.

The heating value (H_p , also called net calorific value, NCV) is the amount of heat released in case of 100% oxidation without considering the condensation enthalpy of the water contained in the flue gas in form of water steam. The gross calorific value (GCV) is defined as the net calorific value (NCV) plus the condensation enthalpy of the water steam (i.e., water formed during combustion and water already contained in the fuel). The gross calorific value (GCV) of biomass of lignocelluloses biomass varies in a small bandwidth around 18.5 MJ/kg only. Some examples are shown in Table 1.

The water (or moisture) content varies greatly within one and between different types of biomass, the season of the year, and the time between harvesting and energetic utilization. The water content is often related to the amount of fresh biomass and therefore describes the amount of water, which is inside the wet biomass. Another term to express the amount of water in biomass is the moisture (or moisture content). Mostly the biomass moisture is related to dry basis: the weight of water contained within the lignocellulosic biomass expressed as a percentage of the weight of the oven dry biomass. Usually the water content of biomass varies between 10% and 50%; some examples are given in Table 1.



Biomass Combustion for Electricity Generation. Figure 2

Schematic of the typical process and supply chains of providing end use out of biomass (in green: process chains, which are the most common ones with regard to electricity generation through combustion of biomass [6])

Water content and heating value are closely related and this relation is linear within some areas. Whereas water free biomass has a gross calorific value of 18.5 MJ/kg, biomass with a water content of 40% has a gross calorific value of only 10 MJ/kg. Usually for air-dry wood or straw, the water content varies between 12% and 20% and therefore the gross calorific value are in a range from 13 to 16 MJ/kg. Wood coming fresh from the forest has a water content of sometimes around 50% and in such cases the heating values is around 8 MJ/kg.

Solid dry lignocellulosic biomass consists mainly of carbon, hydrogen, and oxygen. Carbon is the most important one. For example, wood has a carbon content of almost 50%. Oxygen counts for little more than 40%. The hydrogen content is

usually less than 10%. Other components are nitrogen (N), and trace elements like potassium (K), phosphorous (P), sodium (Na), calcium (Ca), magnesium (Mg), sulfur (S), and chlorine (Cl). Other trace elements like, e.g., silicon (Si) or iron (Fe) are also included in the biomass, but are of less significance.

The ash content of biomass fuel varies within a broad range from approx. 0.5% for, e.g., clean wood without bark up to more than 10% for some straw and cereal assortments. It can go even higher if the fuel is contaminated with impurities (like demolition wood). The ash content of the biomass influences the technology of de-ashing and the combustion technology. Transport and storage of the ash produced also depends on the ash

Biomass Combustion for Electricity Generation. Table 1 Water content, gross calorific value, net calorific value, bulk density, and energy density of biomass fuels [6]

	Water content (wt% w.b.)	GCV (MJ/kg d.b.)	NCV (MJ/kg w.b.)	Bulk density (kg w.b./m ³)	Energy density (MJ/m ³)
Wood pellets	10	19.8	16.4	600	9,840
Woodchips – hardwood – pre-dried	30	19.8	12.2	320	3,900
Woodchips – hardwood	50	19.8	8	450	3,600
Woodchips – softwood – pre-dried	30	19.8	12.2	250	3,050
Woodchips – softwood	50	19.8	8	350	2,800
Grass – high-pressure bales	18	18.4	13.7	200	2,740
Bark	50	20.2	8.2	320	2,620
Triticale (cereals) – high-pressure bales	15	18.7	14.5	175	2,540
Sawdust	50	19.8	8	240	1,920
Straw (winter wheat) – high-pressure bales	15	18.7	14.5	120	1,740
Olive residues (from 2-phase production)	63	21.5	6.1	1,130	6,890
Olive residues (from 3-phase production)	53	22.6	8.5	650	5,530

GCV gross calorific value, NCV net calorific value, d.b. dry basis, w.b. wet basis

content of the fuel. Fuels with low ash content are better suited for thermal utilization than fuels with high ash content, as lower amounts of ash simplify de-ashing, ash transport and storage, as well as utilization and ash disposal. Higher ash content in the fuel usually leads to higher dust emissions and has an influence on the heat exchanger design, the heat exchanger cleaning system, and the dust precipitation technology.

The ash melting temperature is very important for the combustion processes. High process temperatures initiate ash melting, forming solid deposits, which might result in loss of efficiency, plant breakdown and high maintenance. Low ash melting temperatures are characteristic for most of the herbaceous biomass (e.g., straw, rice husk), while woody biomass does normally not cause problems related to ash melting (see Chapter 5.9).

Energy Conversion Technology

In a typical facility “Biomass Combustion for Electricity Generation” the following energy conversion steps are taking place:

1. Conversion from chemical energy into thermal energy (heat)
2. Conversion from thermal energy into mechanical energy (usually rotational energy)
3. Conversion from mechanical energy into electrical energy

The biomass enters into this energy conversion chain in an already pre-processed form. At the end of the energy conversion chain, the electricity is feed into the grid to be transported to the end-users. An additional interface might be a district heating system or a single major heat user (e.g., an industrial company

with a high low temperature heat demand). In this case the system is designed as a combined heat and power station.

Figure 3 shows the general flow diagram and the interfaces of such a biomass to electricity generation facility. According to this there are other interfaces – or better to say – input/outputs into the energy conversion chain: ash, gaseous emissions, energy losses, air and, in most cases, water for cooling purposes.

In order to operate the energy conversion chain described above, different devices are needed. These major plant components are:

- Biomass preprocessing plant (if needed, sometimes not located at the combustion site)
- Biomass storage (open or closed)
- Firing unit
- Steam generator (i.e., boiler)
- Water-steam cycle including feed water pump
- Steam turbine (or steam engine, stirling engine, etc.)
- Generator
- Transformer
- Flue gas treatment facility
- Back cooling facility for the condenser
- Ash disposal

- Other plant components
 - Pumps and auxiliary motors
 - Pipes
 - Fresh water supply
 - Feed water preparation system

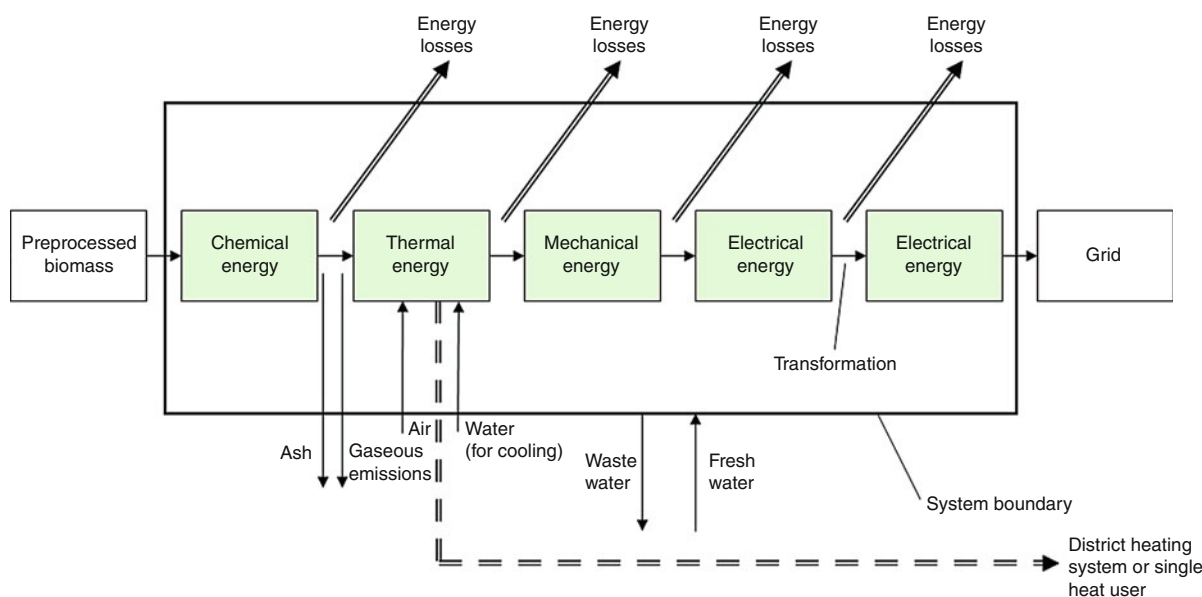
Additionally other units are of great importance for the plant as well, e.g., instrumentation and control system (I&C). But they do not have any direct influence on the energy conversion chain. They are therefore not discussed in further detail here.

Below the major processes and their main components of this energy conversion chain are described in detail.

Biomass Preprocessing

The biomass fuel is usually pre-processed already before it arrives at the combustion site. It is then either burned directly in the form of arrival, or another preprocessing step is taking place at site.

Fuel pretreatment includes all steps necessary to produce an upgraded biofuel from a lignocellulosic biomass resource or from various kinds of organic waste materials (e.g., waste wood, demolition wood). The reasons for such a pretreatment step can be manifold: (1) homogenization for better handling



Biomass Combustion for Electricity Generation. Figure 3
Energy chain of biomass combustion for electricity generation

during storage and feeding into the combustion chamber as well for better combustion and (2) reduction of impurities to improve the fuel resp. the combustion quality. All this finally aims to increase the efficiency, to increase the technical availability, to lower the environmental impacts (emissions, ash volume), and to reduce the investment cost as well as the operation and maintenance cost at the power plant.

For the purpose of large biomass combustion plants, usually the following preprocessing possibilities are of importance:

- Wood fuel (e.g., shrubs, bushes, forest residues, stems or bark up to a diameter of around 50 cm, sawmill residues, demolition wood) is usually chipped in wood chippers. The main purpose of this is to reduce the particle size. Common types of wood chippers are disk chippers and drum chippers.
- Mostly wood is chipped decentralized directly at the harvest site. However, under specific frame conditions also a large-scale centralized chipping can be an economic viable solution.
- Additionally also mills are used to further decrease the particle size of already pre-chipped wood. These could be hammer mills or grinding mills.
- Beside particle size reduction, other pretreatment processes are grading, drying, conditioning, and cooling.
- Pelleting is a combination of several of these processes. The production of pellets might make sense economically under certain frame conditions.

At the end of the various preprocessing steps, the biomass fuel must fulfill the specification required by the combustion device. This specification itself depends on the technology and the individual design. For a typical grate firing device designed for burning woody biomass the specification is given exemplarily in [Table 2](#).

Biomass Storage

The main purpose of a storage facility at a conversion plant is to bridge the time span between the provision of the biofuel free plant gate and its energetic utilization within the plant.

Biological Processes During Storage Biological processes take place during the period where the biomass is stored within the storage facility. The most important process is an aerobic degradation of organic matter (composting). One effect of such degradation is self-heating, which can even result in self-ignition. This may take place if the storage facility is not controlled and maintained properly. The velocity of such self-heating might vary significantly. It depends on the water content, material structure, material density, amount and volume of material, type of storage facility, type of biomass, impurities, storage and ambient temperature, oxygen concentration in the storage facility, and finally the initial amount of bacteria and fungi within the biomass. Another important effect of such biological processes during biomass storage is the appearance of bacteria and fungi itself.

This storing biomass is connected with several risks:

- Loss of matter
- Self-ignition
- Growth of bacteria and fungi, which can be a health risk (e.g., allergic reaction)
- Smelling
- Increase of the water content
- Agglomeration due to freezing
- Decomposition and fine abrasion
- Discharging water, respectively, leakage water

Storage Facilities Biofuels can be stored within ground storage facilities (i.e., open-air) and in buildings. Both types can be found at biomass-to-electricity-generation plants.

Wood, wood chips, etc., are very often stored directly on the ground. Since at the site the biomass is stored only a few hours up to a couple of days, usually no rain or snow protection device is used.

The advantage of storing biofuels in buildings is the better protection against rain or snow. Storage containers can be either simple halls or silos. But always an adequate air ventilation system has to be installed to avoid (1) an unwanted self-heating and (2) condense water generation and the resulting damages to the building.

The storage is charged and discharged either with wheel-mounted front loaders or – in case of larger

Biomass Combustion for Electricity Generation. Table 2 Fuel specification of a typical 5 MW biomass power plant, located in Germany, burning solid residual wood

Size of wood chips						
Class	Mass fraction of relevant particle size area				Extremum 1% outliers	
	Max. 20% (mm)	60–100% (mm)	Max. 20% (mm)	Max. 4% (mm)	Cross-section (cm²)	Length (cm)
G 100 coarse	>63	63–11.2	11.2–1	<1	10	25
	<150					
Heating values of fuels						
Description		Fraction (v%)	Heating value (kWh/kg)		Heating value (MJ/kg)	
Woody landscape conservation crop		0–60	1.9		7.2	
Forest clearance wood		0–30	2.9		10.5	
Forest residues		0–100	2.8		10.4	
Filter spill		0–20	1.8		6.5	
Av. values			2.6		9.36	
Ash content						
Class	Ash content (dry)		Description			
A5	<10%		Normal ash content			
A6	>10%, <15%		Increased ash content			
Bulk density of wood chips						
Class	Limiting value (bulk density in kg dm/m³)		Description			
S 160	<160		Low bulk density (spruce, fir, poplar, willow)			
S 200	160–200		Medium bulk density (pine, larch, birch, alder, maple, elm, Douglas fir)			
S 250	>200		High bulk density (oak, robinia, ash, beech)			
Chemical analysis of dry fuel mixture						
			Design		Variation	
Carbon (C)	Mass-%		50		50.6–54.5	
Hydrogen (H)	Mass-%		5.5		4.7–6.8	
Nitrogen (N)	Mass-%		0.6		0.1–1	
Sulfur (S)	Mass-%		0.1		<0.1	
Chlorine (Cl)	Mass-%		0.1		<0.1	
Ash content (dry)	Mass-%		10		1.5–15	
Sand content	Mass-%		<2			
Other limitations						
Energy density	MJ/m³		2,160–3,000			
	MWh/m³		0.60–0.83			
	MWh/m³/40 min		0.05			
Ash sintering point	°C		>1,000			

facilities – the lorries are directly unloading the biomass onto an automatic feeding system, which can be push floors, different types of screws or crane facilities.

Conversion of Chemical into Thermal Energy

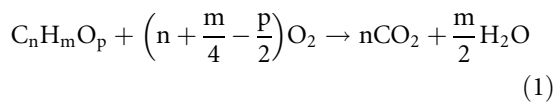
In most of the existing biomass-to-electricity plants, the conversion from chemical energy within the biofuel into thermal energy is realized by combustion. The device in which this takes place is in most cases a boiler – which is a combination of combustion device and steam generator.

However, solid biomass can also be converted into a liquid or gaseous secondary energy carrier. Such energy carriers can be burnt in a boiler as well. However, in most cases they are burnt in other devices. These are either of the following:

- Internal combustion engines (piston motor engines)
- Combustion chambers of gas turbines
- Other forms of devices (not common)

Combustion Ideally combustion can be defined as the complete oxidation of any kind of fuel. Overall, it is an exothermic chemical reaction between a fuel and an oxidant releasing heat. The release of heat can result in the production of light in the form of either glowing or a flame [6, 9, 12].

This chemical reaction can be described by means of a sum formula, wherein the biomass, consisting mainly of carbon (C), oxygen (O), and hydrogen (H), reacts with oxygen (O₂) to form the products carbon dioxide (CO₂) and water (H₂O) (Eq. 1):



This total combustion process can be divided into the following processes: drying, pyrolytic decomposition, gasification, and (complete) oxidation. For the individual particle it is a sequence of these processes; however, all takes place in parallel in the firing device.

During the drying phase, the water within the biofuel is evaporated at temperatures below 150°C. During this phase the biomass is not destroyed. Vaporization requires energy released from the combustions process.

Therefore it lowers the temperature within the combustion chamber by slowing down the combustion process. With regard to biomass, this means that if the water content exceeds a certain percentage (e.g., 60%), the combustion process cannot be maintained: the wet biomass requires too much energy to evaporate the moisture and subsequently to heat the water vapor that the temperatures within the combustion device are reduced below the minimum temperature required to sustain combustion.

Pyrolytic decomposition is defined as thermal degradation at temperatures between 150 and 500°C in the absence of an externally supplied oxidizing agent. The excess air coefficient is zero. A number of variables influence the amount and the properties of the products formed during this endothermic process. These influencing parameters are mainly fuel type, temperature, pressure, heating rate, and reaction time. Fast heating rates favors the formation of products liquid under standard conditions. Slow heating rates provide mainly tar and charcoal as well as low molecular weight gases. Among them, CO and CO₂ are formed in considerable quantities.

Gasification is defined as the conversion of a solid (e.g., charcoal remaining after the pyrolytic decomposition has been taken place) into a gaseous fuel within an endothermic process in the presence of an externally supplied oxidizing agent. The excess air coefficient is between 0 and 1, resulting in a partial oxidation. Gasification takes place within a temperature range starting from approx. 400°C up to more than 1,000°C. The products of the gasification step are combustible product gases, which contain as major components carbon monoxide (CO), carbon dioxide (CO₂), hydrogen (H₂), methane (CH₄), and water (steam) (H₂O). In case air is used for oxidation, also nitrogen (N₂) and nitrogen compounds like nitrogen oxides are included within the product gas. In addition, usually small portions of undesired by-products (like tar, ammonia, hydrogen sulfide, ash) are within the product gas.

Oxidation is the last step and (ideally) means the complete oxidation of the products resulting from the pyrolytic decomposition and the gasification at high temperatures (1,000°C and more) under heat release (i.e., exothermic process). The results are mainly water (H₂O) and carbon dioxide (CO₂). The excess air

coefficient is higher than one. To allow for a full oxidation, the gases to be oxidized and the air have to be mixed quite well.

The efficiency of the overall combustion process – chemical process only – could be described by the combustion efficiency. This efficiency is defined as the ratio of the heat energy generated during combustion and the heating value of the fuel. The (chemical) losses are due to incomplete oxidation with the result that energy is still contained in some un-oxidized components (e.g., char, tar, unburned gases). Today combustion processes in power plants or CHPs achieve combustion efficiencies of significantly more than 95% (95–98%). However, the performance of the combustion process is usually not expressed in terms of efficiency. It is controlled by analysis of the ash – stating the unburned matter – and the flue gas (i.e., the un-oxidized organic compounds).

All other losses, in form of heat – e.g., with the flue gas, with the ash, from the boiler or the gas turbine casing – are not considered here since they are related to the technical devices.

Thermal Cycles The combustion of the solid, liquid, or gaseous fuel for electricity generation is usually part of a thermal cycle, in which a media is undergoing phase changes between the liquid and the gas phase and where energy is added and released in certain parts of the cycle. Such cycles are divided into open and closed thermal processes.

Open cycles are commonly applied for gaseous and liquid fuels since they have fewer impurities than solid biomass. They are realized in internal combustion engines and gas turbines. The fuel is either burned directly inside an internal combustion engine, which is operated cyclically (like a four stroke or two stroke engine), or it is burned continuously in an external combustion chamber and then led through a gas turbine for expansion. The working fluid does not circulate through the system; therefore it is not a true cycle. The direct use of solid biomass fuels in internal combustion engines is technically not feasible and their application in open cycle gas turbines is regarded as complex.

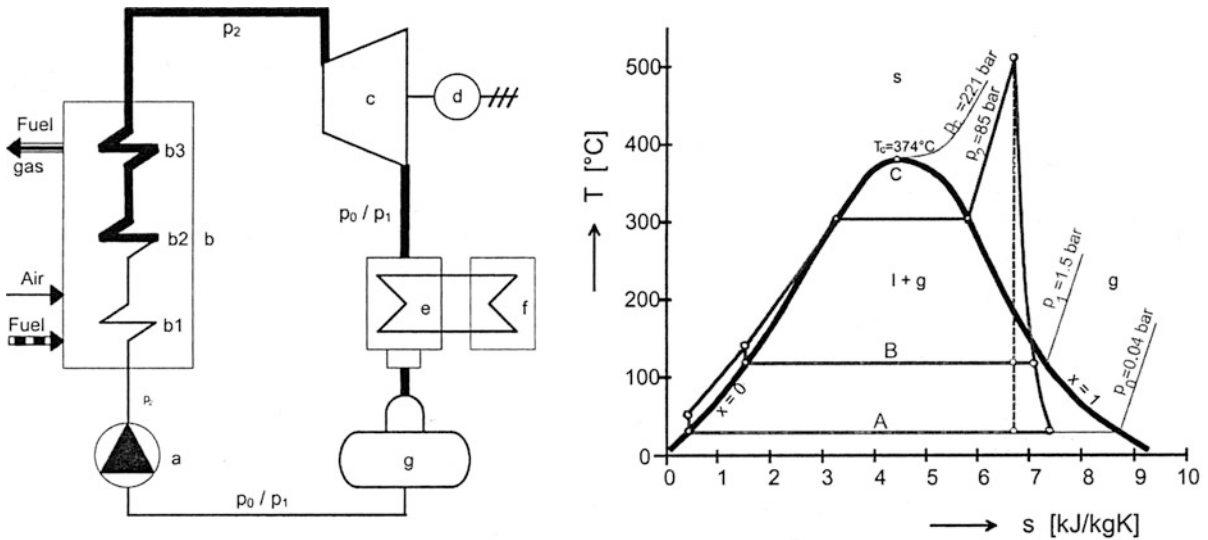
In closed thermal cycles the combustion process and the power generation cycle are physically separated by a heat transfer device between the

combustion and the process medium used within the secondary cycle. Due to the separation between fuel and power generation equipment, the latter is solely in contact with a clean process medium and thus undesired elements like fuel, ash, tar, and flue gas are not harming. Hence, closed cycles are well suited for solid fuels and widely applied for power production from biomass or waste.

The cycle mostly applied for electricity generation from solid biofuels is the Clausius Rankine Process [11] (Fig. 4). Water at low pressure is transferred with a feed pump to a higher pressure level. The pressurized water is then heated up to the evaporation temperature in the boiler, then evaporated to saturated steam, and finally superheated in the superheater section to dry steam. This steam is then expanded to the back pressure in the turbine, which provides kinetic energy to the generator. The back-pressure steam is led to the condenser, where the remaining condensation enthalpy needs to be transferred to the cooling medium. Finally water at low pressure leaves the condenser and is transported to the feed pump to start the cycle again.

Basically, thermal efficiency of the thermal cycle depends on the temperature difference of the hot steam and the “cold” water (Carnot law). As an example, using Carnot’s law, for a typical rankine cycle with steam temperature of 543°C (816 K) and a temperature of the condensed water of 23°C (296 K), the maximum theoretical efficiency can be calculated as with 64%. However, typical thermal efficiencies of realized Clausius Rankine processes in biomass power plants are in the range of 30 to a maximum of 40% (i.e., with own consumption and without any mechanical losses). This is lower as in modern state-of-the-art large-scale coal-fired thermal power plants. Here the Clausius Rankine cycle can reach efficiencies up to 50% or more. This is mostly because the temperature differences between the upper and the lower side of the thermal cycle can be increased due to the utilization of more sophisticated material.

Another closed cycle sometimes used in biomass combustion facilities is the Organic Rankine Cycle (ORC). This cycle is similar to the Rankine Cycle. However, instead of water an organic fluid with a lower boiling temperature is used as a process medium. This enables operation with heat sources of relatively low temperatures (e.g., 90–150°C); this is the



Biomass Combustion for Electricity Generation. Figure 4

Flow and T/s diagrams of back-pressure plants based on the Rankine cycle [12]. *Left:* Principle of a power plant based on a Rankine cycle with steam superheating. *Right:* In the T/s -diagram (temperature versus entropy). Case A describes a condensing plant with component f in the flow diagram being an air cooler or a cooling tower for heat transfer to the ambient. Case B describes a back-pressure plant with utilization, of the heat at a higher temperature level, hence component f corresponds to a heat exchanger used for heating purposes or process heat. In a back-pressure plant, the condensation temperature $T_6 = T_1$ is increased to enable heat utilization, thus reducing the electrical efficiency. For small turbines, the back-pressure steam needs to be saturated, as droplets are not allowed. Hence point 6 in the T/s -diagram needs to be on the condensation line, thus resulting in a reduced efficiency. Components in the flow diagram: a = feed water pump, b = boiler with b1 = water preheater, b2 = evaporator, and b3 = superheater, c = steam turbine, d = generator, e = condenser, f = heat exchanger to transfer condensation enthalpy in a secondary circuit to the ambient (case A corresponding to a condensing plant) or to a heat consumer (case B corresponding to a back-pressure plant), g = feed water tank. Abbreviations in the T/s -diagram: s = entropy, t = temperature, l = liquid, g = gas (vapor), s = supercritical, c = critical point, p = pressure, p_2 = high pressure of the live steam, p_0 = back pressure for a condensing plant A, p_1 = back pressure for back-pressure plant B. 1–2 Adiabatic pressure increase of the water in the feed pump. 2–3 Heating of the water to evaporation temperature in the water preheater. 3–4 Evaporation of the water in the evaporator in the boiler. 4–5 Superheating of the steam in the superheater. 5–6 Isentropic expansion of the steam (ideally). 6–7 Polytropic expansion of the steam in the turbine (real process). 6–1 Condensation of the steam, with either heat transfer in a secondary circuit either to ambient (condensing plant) or heat utilization (back pressure plant)

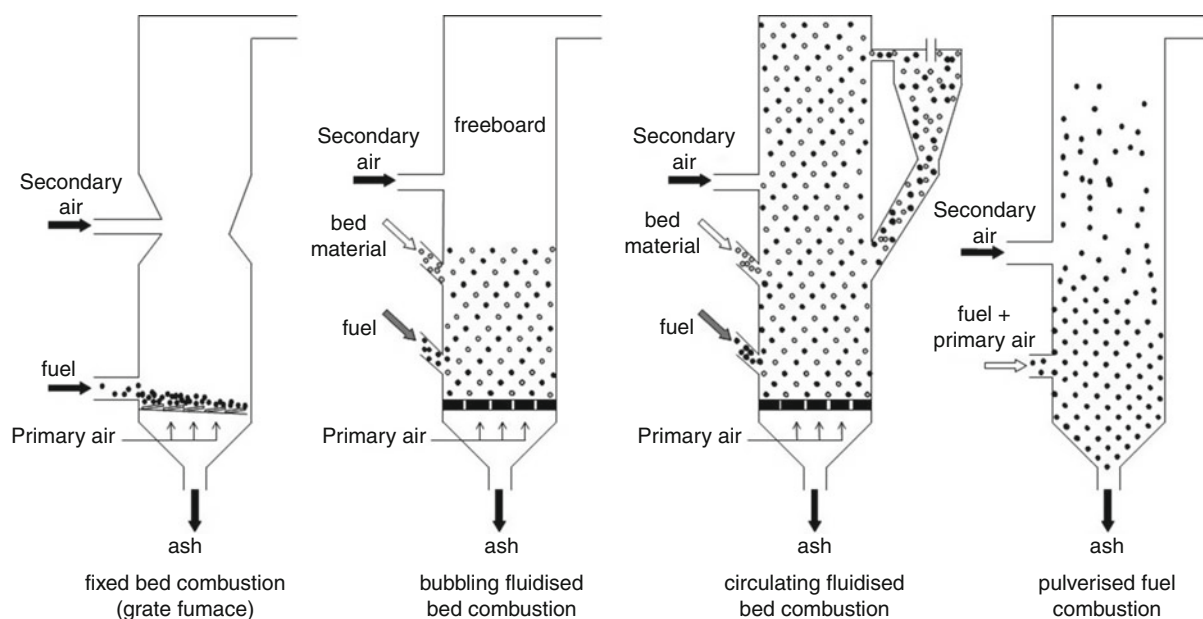
reason why this cycle is often used for electricity generation from geothermal energy. ORC processes within the biomass sector are sometimes added after a “classical” Rankine Cycle to make use of the residual heat in the flue gas at low temperature and use it for electricity generation.

Thermal efficiency of the ORC process is significantly lower compared to the Clausius Rankine process, being in the range between 12% and 17% (process only, excluding own consumption and mechanical losses of the turbine). This is due to the lower

temperature of the driving heat source and therefore the lower temperature differences used hereunder.

Technical Devices Combustion of solid biofuels in biomass-to-electricity generation facilities usually takes place in boilers. The differentiation is made by the technology of the firing system into:

- Fixed bed combustion (usually on a grate)
- Fluidized bed combustion
- Pulverized fuel combustion



Biomass Combustion for Electricity Generation. Figure 5
Principal combustion technologies for biomass [12]

Figure 5 shows the main principles.

All of the boiler types have in common that the biomass is burned and then the thermal energy is used to heat water running through pipes – mostly inside the boiler. After preheating (economizer), the water is heated up to the point of evaporation, evaporated, and then superheated. The relevant tubes are located in different parts of the boiler.

The energy losses within such a boiler are of different type and dependent on the boiler type, size, and material, and the fuel type mainly.

- Dry flue gas loss is the sensible heat loss that is due to the temperature difference between flue gas and the inlet air temperature (the flue gas carries heat up the stack). It is a function of excess air as well as the flue gas temperature and combustion air temperature.
- Latent heat loss is due to the water vapor in the flue gas leaving the boiler without being condensed (not used condensation enthalpy). It comes from (a) the combustion of hydrogen (respectively hydrocarbons) in the fuel and (b) water contained in the fuel (“Moisture-in-fuel loss”) and (c) water in the combustion air. Significant levels of water are found naturally in biomass.

- Casing losses are the radiant and convective heat losses from the boiler casing.
- Losses due to incomplete combustion (unburned matter in ash and flue gas).
- Other losses are caused by air or flue gas leaks, and by heat in the ash.

Boiler efficiency (including the firing system) is the ratio of heat absorbed in steam to the heat supplied in the fuel. Modern biomass boilers (from 20 MW_{th} upwards) can achieve energy efficiencies of 90–95%. As for all solid fuel combustion systems, the boiler efficiency is mostly related to the net calorific value.

Below the most important types of boilers are discussed in detail.

Fixed Bed Combustion Systems Fixed bed combustion systems in biomass power plants are usually realized in form of a grate firing system. Smaller furnaces and boilers (a few MW_{th}) can be realized as well with underfeed firing. Primary air passes through a fixed bed, in which drying, pyrolytic decomposition, and gasification take place. The combustible gases are burned after secondary air has been added usually in a combustion zone separate from the fuel bed.

Such kind of combustion usually takes place on grates, of which various types are available: fixed grates, moving grates, traveling grates, rotating grates, and vibrating grates. The grates can be horizontal or inclined. The correct selection of the grate depends on the fuel properties and the size of the plant.

As a standard rule, grate firing is appropriate for fuels with a water content up to 60%, varying (but not smaller than approximately 2 mm) particle sizes, and high ash content. Thus, mixtures of wood and other type of biomass can be used.

Of great importance is always to allow a homogenous distribution of the fuel to keep the bed of embers at the intended location of the grate surface – over the full width, but only in a well-defined zone in the moving direction. A homogenous fuel layer is important to guarantee an equal primary air supply over the various grate areas. Inhomogeneous air supply may cause slugging, higher fly-ash amounts, and may increase the excess oxygen needed for a complete combustion resulting in boiler heat losses. Furthermore, the transport of the fuel over the grate has to be as smooth and homogenous as possible in order to keep the bed of embers calm and homogenous, to avoid the formation of holes, and to avoid the release of fly ash and unburned particles as much as possible.

Fluidized Bed Combustion Systems In fluidized bed combustion, the solid biofuels are suspended during the combustion process within a moving gas and particle stream, called the bed. The result is a turbulent mixing of gas and solids, which provides very effective chemical reactions and heat transfer.

The core of this technology is the fluidized bed reactor. A fluid (gas or liquid) is passed through a granular solid material at high enough velocities to suspend the solid. The reactor is usually a cylindrical vessel with a perforated bottom plate filled with a suspension bed of hot, inert, and granular material. Common bed materials for combustion are, e.g., sand.

Through the air distribution plate, primary combustion air enters the reactor from below. When the slackening velocity (minimum velocity to de-lock the bed) is reached, the bed expands and the gas/solids mixture behaves like a fluid. This process is known as fluidization. With further increasing gas flow the bed will change its fluid dynamic behavior: gas bubbles

form in the bed, they will agglomerate to larger ones, the bed begins to slug, finally when one bubble reaches the diameter of the reactor, it moves up the bed, showing a piston-like behavior, an extreme form of a slugging bed. Depending on the fluid dynamic regime during operation, the reactor is called a bubbling fluidized bed, etc.

Intense heat transfer and mixing provides good conditions for complete combustion with low excess air demand. Between 650°C and 900°C, the combustion temperature is usually low in order to prevent ash sintering in the bed. Keeping the temperature in such lower ranges can be achieved by, e.g., (1) heat exchanger surfaces or (2) flue gas circulation.

Fluidized bed combustion plants are in widespread use, since the fluidized bed can deal flexibly with various fuel types, including very high water content, as a result of the good mixing achieved. Different kinds of solid fuels like woody biomass, coal, and special kind of waste (e.g., RDF) can be burned. Fluidized beds are as well the standard technology for burning sludges (e.g., sewage sludge from waste water treatment). However, the fluidized bed performance is sensitive toward particle size and inert impurities in the fuel. Therefore, usually an appropriate fuel pretreatment system for particle size reduction and separation of metal parts and stones is necessary. Particle sizes between 40 and 80 mm are common for woody biomass. Further considerations are, e.g., regarding high alkali biomass fuels (e.g., straw), due to possible ash agglomeration.

During start-up time of fluidized beds, which can take longer period of times (8 till 15 h), oil or gas burners are used. Due to higher specific investment of the overall plant, fluidized bed combustion is more common in larger applications (usually nominal thermal boiler capacity above 20 MW_{th}). With regard to emissions, low NO_x emissions can be achieved due to good air staging, good mixing, and low requirement of excess air. Low excess air quantities reduce the overall flue gas flow and increase the overall combustion efficiency. Usually the flue gas leaves the reactor with high dust loads. Therefore efficient dust precipitators and boiler cleaning is necessary. Bed material is also lost with the ash, making it necessary to periodically add new material to the plant, even though part of the bed material inside the ash can be separated from the fine particles and sand in air classifiers.

Different types of fluidized bed combustions are distinguished: (1) stationary fluidized bed combustion and (2) circulating fluidized bed combustion.

Stationary fluidized bed combustion has the main principle that the flow velocity of the gas in the vessel is between the slackening velocity (minimum velocity to enable fluidization) and the floating velocity of a single particle of the bed material. Usually the flow velocity of the gas is between 5 and 15 times the slackening velocities. In such cases a clearly defined fluidized bed usually with a thickness between 1 and 2 m is created.

In circulating fluidized beds the gas velocity is significantly above the floating velocity of the individual particles. Due to this there is no clearly defined bed surface: the fluidized bed expanded in the whole vessel. Due to the high gas velocity bed material is entrained out of the vessel and has therefore to be recirculated back to the vessel, after it has been separated in one or several cyclones from the gas flow.

Pulverized Fuel Combustion Systems In pulverized fuel combustion, fuels such as saw dust and fine shavings are pneumatically injected into the combustion room. The transportation air is used as primary air.

When starting a pulverized fuel combustion reactor, usually an auxiliary burner is used for preheating. After the temperature in the boiler has achieved a certain level, biomass is injected through a burner.

Fuel quality has to be quite constant. Particle size is usually limited between 10 and 20 mm. Fuel moisture content should not exceed 20%. Due to the explosion-like combustion of the fine biomass particles, the fuel feeding needs to be controlled very carefully.

Fuel/air mixtures are usually injected tangentially into the combustion room to establish a rotational flow. The rotational flow can be supported by flue gas recirculation in the combustion chamber.

Excursus: Co-firing Concepts

Co-firing means that biomass and fossil fuels are being used jointly in a plant to produce electricity and/or heat.

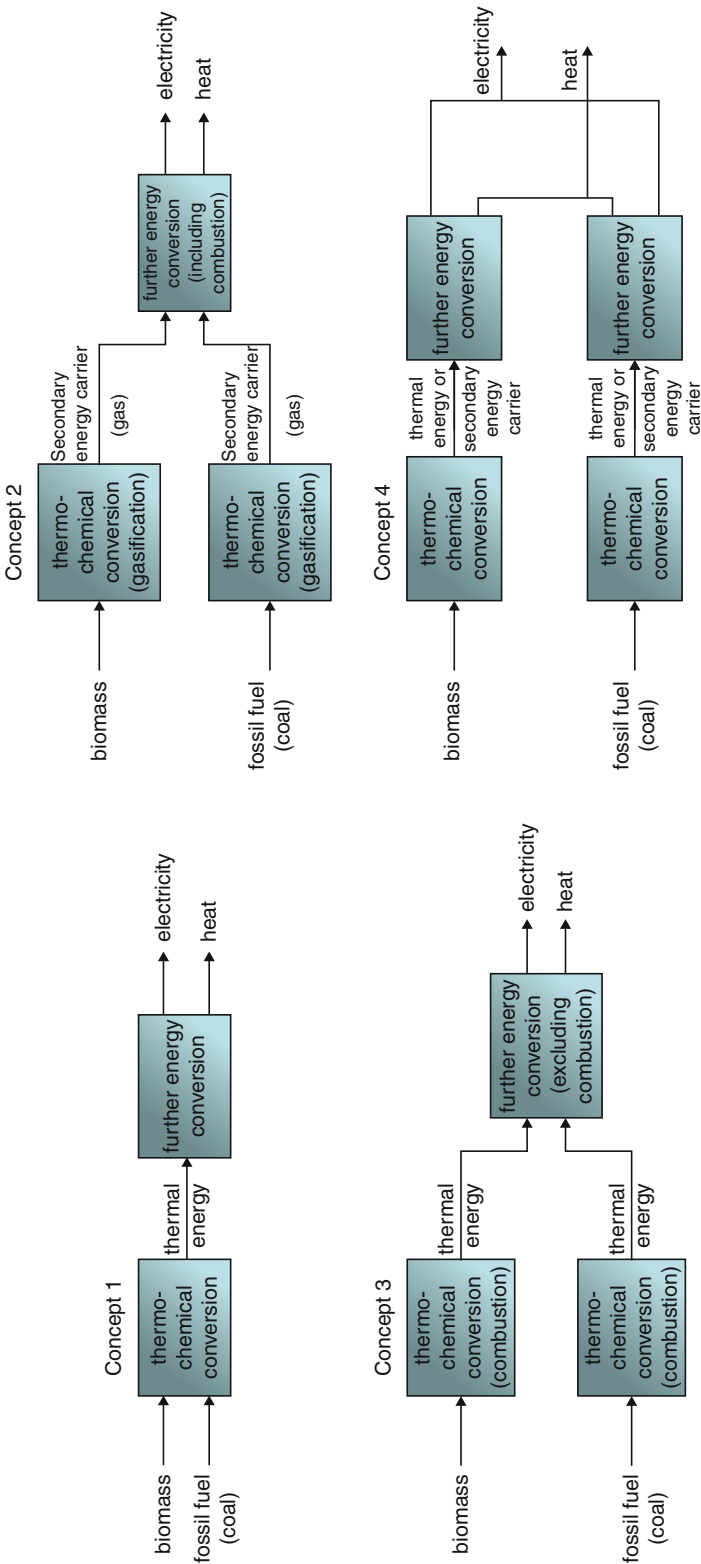
Such co-firing can provide a reasonable attractive option for the utilization of biomass for the generation of power and in some cases heat. Co-firing makes use of the extensive infrastructure associated with an existing

power plant system based on fossil fuel energy, and requires only relatively modest additional capital investment.

The principal driver for the increasing amount of co-fired biomass materials in new and existing coal boiler plants is that co-firing is regarded as representing a very attractive option for biomass utilization, and therefore of the delivery of electric energy out of renewable energy, in terms of the capital cost requirement, security of supply, power generation efficiency, and generation cost.

The great majority of biomass co-firing worldwide is carried out in large pulverized coal power boilers, and the focus in this section is very much on this type of plant. The basic co-firing options can be categorized according to Fig. 6.

- **Concept 1: direct co-firing.** Under this concept, biomass and fossil fuel is being burned in the same conversion unit; usually it means that the biomass is fed directly to the coal firing system of the boiler. This co-firing approach can be implemented in a number of ways. The first option involves the mixing of the biofuel with the coal upstream of the coal feeders, and generally within the coal conveying system. The mixed fuel is then processed through the installed coal milling and firing system. This is the simplest option and involves the lowest capital cost. This approach has been applied widely for co-firing biomass in granular, pelletized, and dust forms, generally at relatively low co-firing ratios. The second option involves separate handling, metering, and comminuting of the biofuel and injection into the pulverized fuel pipe work upstream of the burners or at the burners. This option can permit co-firing at elevated levels. The third option involves the separate handling and comminuting of the biofuel with combustion through a number of dedicated burners. This approach involves significant modification of the combustion equipment and the boiler, and represents the highest capital cost direct co-firing option. It is, in principle, possible to inject the pre-milled biomass into the upper part of the combustion room as a re-burn fuel for NO_x emission control; however, this option needs significant further development prior to full scale implementation. Some test work has been carried out in small-scale test facilities.



Biomass Combustion for Electricity Generation. Figure 6
Biomass co-firing concepts

- Concept 2: indirect co-firing. This concept involves the conversion of the biomass and the fossil fuel each in a separate unit into a secondary energy carrier. Usually this is a gasifier. Then these two secondary energy carriers are fed into one combustion system and then to go on with the further energy conversion steps. The usual system hereunder is the gasification of the biomass and the combustion of the product fuel gas in the boiler or gas turbine.
- Concept 3: parallel combustion. In this case, biomass and fossil fuel are first being converted thermochemically separately. The result of these two separate conversions is thermal energy (heat). This heat is then converted in further conversion steps to electricity and heat. Usually this process is called parallel combustion. Parallel firing involves the installation of a separate combustor for the biomass to produce steam, which, in turn, is used in the coal-fired power plant steam circuit. Although parallel firing installations involve significantly higher capital investment than direct co-combustion systems, they may have advantages such as the possibility to use relatively difficult fuels with high alkali metal and chlorine contents and the production of separate coal and biomass ash streams.
- Concept 4: separate combustion and conversion. Under this concept, the biomass and the fossil fuel are utilized for electricity/heat generation in two separate units, but at the same power plant site. Therefore, only several BoP (balance of plant) parts of the power plant site are used jointly like, e.g., grid connection, road infrastructure, and water supply. A separate combustion and separate further conversion of the secondary energy or heat into electricity and heat means that only the final energy carriers (electricity and heat) are flowing together. This is usual praxis in a number of biomass combustion plants. The advantage is that the infrastructure on site can be used by both plants as well as several selected BoP components.

Conversion from Thermal to Mechanical Energy

The conversion from thermal energy into mechanical energy is performed in devices, which can generally be

divided into those of turbine type and those of engine type:

- Steam turbines
- Engines
 - Steam engines
 - Stirling engines

These different types of conversion devices are discussed below.

Steam Turbines Mostly applied in biomass to electricity generation systems is the steam turbine. Steam turbines are by definition fluid flow engines, in which the energy of a flowing working fluid (e.g., steam) is converted into kinetic energy and then in mechanical energy of the turbine shaft. Usually the turbine shaft is connected to a generator, in which the rotational mechanical energy is converted into electrical energy.

Steam turbines are available within a large range of different capacities, from few 100 kW (mechanical energy), commonly several 10s to several 100s of MW, up to the largest one with roughly 1,600 MW, currently under construction for the Olkiluoto III nuclear power plant in Finland. Within the biomass sector steam turbines in the range of several MW up to some 50–100 MW are most common.

A typical steam turbine consists of shaft, rotating shuffle wheel(s), fixed shuffle wheel(s), and the turbine casing. Fixed and rotating shuffle wheel are together forming one turbine step, whereby usually – apart of very small turbines – a turbine consists of several steps.

The working fluid flows usually in axial direction and only sometimes in radial direction between the annular gap between chamber and shaft, where the shuffle wheels are located.

Different types of steam turbine exist:

- Back-pressure steam turbines, in which the total waste heat from the condensation of the steam is utilized; the back pressure corresponds to the temperature needed for heat utilization (i.e., close to or greater than 1 bar).
- Condensing turbines are used in power plants without heat utilization; the back pressure and the corresponding temperature are as low as possible to achieve maximum efficiency, and hence the temperature is close to ambient temperature while the back pressure is significantly below 0.1 bar.

- Extraction turbines allow a power plant with variable heat output. Such a turbine enables a variable extraction of steam at an intermediate pressure and temperature level for heat utilization, with the remaining steam being utilized to drive an additional low-pressure section of the turbine in condensing mode.

Energy losses of the steam turbine are (1) heat losses through the casing, (2) steam leakages, and (3) energy losses with the steam flow leaving the turbine, due to non-ideal fluid dynamics while converting the energy of the steam to mechanical energy. In modern state-of-the-art steam power plants in the range of several 100 MW such losses total to less than 8%. For typical power plants in the range of several MW up to several tens of MW (this is the most common range of biomass power plants), such losses sum up to usually between 15% and 22%. Thus, the overall efficiency of the steam turbine in such typical biomass power plant defined as the ratio between mechanical energy at the turbine shaft and the difference of the thermal energy at the inlet and outlet point of the turbine (enthalpy difference) is between 78% and 85%.

Engines Steam piston engines have a similar working principle as other engines. They are available with an installed power between 25 kW up to 1.5 MW per unit. Very often the plant size is larger and in such a case several units are simply added in series. Typical mechanical efficiencies are in the range of 6–10% for single stage pistons and 12–20% for multistage engines. For this reason such devices are only used in CHP mode.

Stirling engines are indirectly fired gas engines with air, helium, or hydrogen as a process medium used within a closed cycle. External heat is transferred to the gas, followed by forced cooling of the gas. Expansion and compression of the medium inside the chamber are allowed over a piston. A Stirling engine is the thermodynamic ideal process for transforming heat into mechanical energy. It has thus the same theoretical efficiency as the Carnot process. In addition, in contrast to the Carnot process, it can actually be realized. However, in practical application the theoretical high efficiency

is reduced by friction, limited heat transfer and heat recuperation, pressure losses, and other influences. Thus the actual efficiency for power production is only in the range of 15–25%. Additionally such devices are only limitedly available in the market.

Conversion from Mechanical to Electrical Energy

The conversion from mechanical into electrical energy takes place within the generator. The basic energy conversion principle is electromagnetic induction [3]. Such principle means that if an electric conductor, like a copper wire, moves through a magnetic field, an electric current is induced within the conductor. Thus the mechanical energy of the moving wire is converted into the electric energy of the current that flows in the wire. The main elements of the generator are the rotor and the stator. The stator is the fixed part and is wound with wires through which alternate electrical current is flowing, in which an alternate voltage is induced. The stator is usually connected directly or indirectly to the grid and therefore also the frequency of the electrical current in the stator is either the grid frequency or in any defined relation to it.

The rotating magnetic field induces an AC voltage in the stator windings. The rotor is also with wire, and this wire is rotating in the magnetic field inducing electric current in the stator. The rotor is connected usually mechanically via a gearbox with the rotating axes of the engine or turbine. The gearbox allows that the rotational speed of the rotor fits to the frequency of the stator.

Although different types of generators are used for different applications, in biomass to electricity generation as in other thermal power plant synchronous single-fed generators are applied in general. Other types are, e.g., asynchronous or induction single-fed generators, doubly fed generator, or brushless wound-rotor doubly-fed generator.

Independently from the type of generator, the electric power at the output of the generator has a fixed voltage level, which can be chosen among the typical standard voltage classes. Typical voltage levels for biomass combustion plants up to 20 MW_{el} are 400 V, 6.3 kV, and 11 kV.

Energy conversion efficiencies in the electrical generator are usually quite high. Losses mainly occur in form of heat, due to the wire resistance, and mechanical losses in the bearings of the rotor. The efficiency of modern synchronous generators is usually in the range between 96% (1,500 kVA at biogas plants, $\cos \phi = 0.8$) and 98% in large power plants.

Electric Energy Transformation

Usually the generator generates electricity at a typical voltage level. But the voltage level of the (local, regional, or supra-regional) grid is different in most cases. The electricity generated is therefore feed into the grid via a transformer station, whose main purpose is to transform the voltage coming from the generator into the voltage of the grid. Losses in the transformer are usually low and in the range of 1–3% of the input electricity. The losses can be divided into copper losses and iron losses. They are resulting out of (1) winding resistance, (2) hysteresis, (3) eddy currents, (4) magnetostriction, (5) mechanical losses, and (6) stray losses [4].

Other Plant Components

Within this chapter, additional system elements needed within an electricity generation plant operating based on biomass are discussed in detail.

Cooling Facility After the steam has flown through the steam turbine, it has to be cooled down. Thus, cooling water circulates around the tubes of the condenser and by this means the low-pressure steam after the turbine is cooled down and condensed.

The heat absorbed by the circulating cooling water in the condenser tubes must also be removed to maintain the ability of the water to cool as it circulates. The easiest option is getting the cooling water from a river or the sea and pumping the warm water back to the river or the sea. However, since sea water is not available at most power plant sites, and environmental restrictions limit temperature increase of rivers, waste heat is in most cases transferred to the atmosphere based on a cooling tower, or a combination of river and cooling tower cooling is realized. The warm water is pumped from the condenser through the cooling tower. A wet (or open) cooling tower reduces the temperature of the

water in direct contact to the air, mainly by evaporation of a part of the water.

There are natural (air) draft and mechanical draft towers. The latter uses power driven fan engines to force or draw air through the tower. Within this type it can be differed between (1) induced draft, wherein a mechanical draft tower with a fan at the discharge pulls air through tower, and (2) forced draft, which has a blower type fan at the intake.

A dry (or closed) tower is a water–air heat exchanger, with a fan to increase air circulation. If the availability of water is not an issue at the location, usually a wet cooling tower is used, since lower temperatures are achieved. At other sites, where water availability is critical, or the formation of clouds has to be avoided, dry cooling towers are applied, which usually drops down the efficiency of the plant.

Flue Gas Treatment After the combustion, the flue gas is treated usually in different ways before it is emitted into the atmosphere due to legal obligations. All equipment and measures to treat the flue gas between the boiler outlet and the atmosphere is named together flue-gas-treatment-facility. The core objective of this facility is to reduce the emissions to a level that the power plant facility at the location has to fulfill.

To achieve the desired emission level, different measures are applied. They are subdivided in primary (i.e., directly influencing the combustion process itself) and secondary measures. Primary measures can be found under section “[Gaseous Emissions](#)”. Secondary emissions reduction measures are part of the flue-gas-treatment-facility.

Flue gas treatment measures in biomass power plants derive from coal power plants. In a standard coal combustion plant, the flue-gas-treatment-facility consists of (in this sequence, with regard to the flow direction of the flue gas):

- A particle control and reduction facility
- NO_x control and reduction facility
- SO_2 reduction facility

Whether all of the above components or only some of them are part of the flue-gas-treatment-facility of a biomass combustion plant and which specific type of emission reduction technology has to be selected depend

on the biomass characteristics (chemical composition, particle size, etc.), the combustion technology, and the environmental regulations to be applied. In most cases, the flue-gas-treatment-facility of a biomass combustion plant is much simpler:

- For power plants burning only clean (natural) wood an electrostatic precipitator is sufficient to meet the emission limits for particulate matter.
- Larger power plants, burning contaminated wood as well, often apply dry sorption by spraying, e.g., calcium hydroxide into the flue gases and filtering them within a bag filter.

The principles of flue-gas-treatment-facilities are explained below.

Particle Control Systems For meeting the limits for particulate matter emissions the following reduction technologies are used commonly: cyclones, multicyclones, electrostatic precipitators, and bag house filters. They are discussed below.

Within a cyclone for particle separation, the flue gas and the solid particles are exposed to centrifugal forces. Due to these forces, the particles hit the wall of the cyclone and slide down into a container. The cleaned gas leaves the cyclone on the upper side.

In multicyclones, several cyclones are used in parallel. This is because the efficiency of a cyclone can be improved by increasing the centrifugal forces through a reduction of the cyclone diameter. However, this has the disadvantage that the throughput through one cyclone is reduced. To compensate this drawback some small cyclones are installed in parallel. The consequence are, obviously, higher cost due to the larger number of cyclones – even though each individual one is smaller – and a higher energy consumption due to the higher pressure drop in a smaller compared to a larger cyclone. Nevertheless often multicyclones are state-of-the-art technology and used frequently.

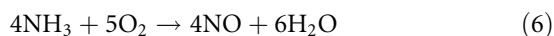
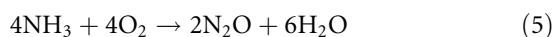
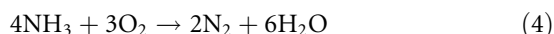
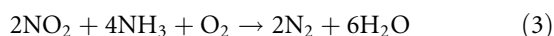
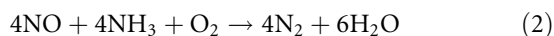
The principle of operation of an electrostatic precipitator is that the particles are first electrically charged and second exposed to an electric field in which they are attracted to an electrode. This electrode is cleaned periodically by means of vibration with the consequence that the dust falls off the electrode into a collection unit. Electrostatic precipitators are state-

of-the-art technology and used commonly in large-scale units.

Bag house filters consist of a filter or cloth, tightly woven from special fibers and hung up in a closed construction through which the flue gas passes. Usually the separation efficiency of bag house filters is quite high, even with flue gas at low flow rates and high particle content. Because the particles settle on the cloth and form a particle layer (i.e., filter cake), the pressure drop between the two sides of the cloth increases during operation and therefore the cloth has to be cleaned periodically. One possibility is to use pressurized air passed through the cloth in reverse direction, removing the particle layer falling down to the bottom of the filter casing. This flue gas treatment technology is state-of-the-art technology and commonly used in medium scale units [6, 12].

NO_x Control Systems Secondary NO_x-emission control and reduction measures in biomass combustion facilities are mostly selective catalytic reduction (SCR) or selective non-catalytic reduction (SNCR). Both types have in common that a reducing agent is injected (e.g., ammonia (NH₃) or urea) to reduce NO_x to N₂, with or without a catalyst.

In case of using ammonia, the stoichiometric equations are as follows [6]:



Of the reactions listed above, the first two are the desired ones and the last three are undesired reactions.

Equations 2 and 3 take place within a temperature range of 220–270°C. If urea is used, the temperature level has to be increased to 400–450°C. The reason to realize a non-catalytic instead of catalytic reduction is mainly the amount of catalyst needed and the associated cost. For such a non-catalytic reduction, the reactions above described are taking place at temperatures between 850°C and 950°C, whereby for wood a temperature range between 840°C and 920°C has

proved most appropriate. Just due to the high temperature, there is no need for a catalyst.

Both types of reduction facilities have reduction efficiencies – defined as the amount of NO_x separated out of the flue gas related to the total amount of NO_x contained in the flue gas before entering the flue gas treatment facility – between 60% and up to 95% in biomass combustion applications. The efficiency depends very much on the quality of control and regulating the temperature. If the temperature is too high, ammonia is oxidized to NO ; if the temperature is too low, ammonia does not react at all and is emitted together with NO_2 .

SO₂ Control Systems SO_x emissions from biomass combustion facilities are usually at a very low level and sulfur is emitted basically as SO_2 . Due to the low content of sulfur in wood, the combustion of wood usually results in little SO_2 emissions making secondary measures for flue gas treatment unnecessary. However, there are certain biomass types (e.g., straw, grass, Miscanthus) for which the SO_2 emissions can be significantly and in such a case SO_2 reduction measures must be applied.

The typical secondary measure for SO_2 reduction is scrubbing the flue gas with water containing finely grounded limestone (i.e., limestone wet scrubber). The flue gas, from which the solid fly-ash particles have already been removed, passes through a tower where the scrubbing slurry containing water and limestone particles is pumped through countercurrent. The scrubber vessel can be realized as a spray tower with multiple sprays and a mist eliminator. Other approaches are characterized by a packing with a very high opening integrated within the tower or a specialized bubbler designs.

Other Emission Control Systems Depending on the type of biomass fuels, other secondary control and reduction measures might have to be applied:

- Straw, for example, has a high content of chlorine (Cl), which one finds later in the flue gas as hydrogen chloride (HCl). In case primary measures and, e.g., binding the chlorine into the ash is not sufficient to reach the required emission limits for HCl, combined fine dust separation with dry sorption or with a wet washing can be applied.

- Sometimes it might be necessary to include secondary reduction measures to reduce dioxins and furans. Quite frequently this is combined with the SCR facility with a catalytic oxidation of particle-binding and filter-passing dioxins. Other possibilities for particle-binding dioxins are special dioxin filters.
- By condensing the water within the flue gas, the overall efficiency of the power plant can be improved since the latent energy of the water is used. In addition, this allows reducing or avoiding vapor clouds in the air, usually regarded as a negative visual impact especially in touristic areas. Furthermore, within such a flue gas condensing unit a cleaning effect is realized (e.g., particulate matter). The operating principle is that the flue gas is cooled below the dew-point, by which a part of the water steam is condensed. The energy set free during this condensing process can be used as usable heat. The efficiency of the condensing unit depends on the amount of excess air, the water content of the biomass fuel, the flue gas temperature, and the lower temperature level of the usable heat.

Chimney The cleaned flue gas is finally emitted to the atmosphere via a chimney or smoke-stack. Chimneys are typically vertical structures to ensure that the gases flow smoothly. Additionally they draw air into the combustion what is known as the stack or chimney effect. This effects uses the density difference between the hot flue gas inside the chimney (hotter means lower density) and the colder air outside the chimney (i.e., air with a higher density). Due to this density difference, the flue gas is flowing upward within the chimney. Thus the reason for the height of the chimney is not only to emit the flue gas to higher air levels so that it is dispersed better, but also to create sufficient pressure difference between hot flue gas and the outside air.

For biomass power plants with 5 and 20 MW_{el}, chimneys have heights of 30–50 m. Usually they are constructed in the outer part out of concrete. Inside this supporting structure, a jacket pipe per boiler is installed in which the flue gas is flowing. It is built out of flue gas resistant material.

Ash

Burning of solid biomass is inevitably related to the generation of ash as a by-product. Ash, produced in large-scale biomass combustion plants, can usually be separated in three different fractions [15]:

- Grate ash. Usually this fraction consists of the mineral residual of the biomass feedstock produced on the grate or within the circulating fluidized bed. In addition, inert material (i.e., mainly soil) which has been within the biomass fuel can be found herein. Beside this sintered ash particles and slack stones – particularly in the case of straw and bark – might be found. The share of the grate ash related to the total amount of ash is usually in the range of 60–90%.
- Cyclone ash. Cyclone ashes are fine particles entrained with the flue gas stream. Usually this ash fraction originates from inorganic matter like, e.g., salts and silicates being a part of the organic structure of plants. This ash fraction can be found as dust in turnaround chambers and in the heat transfer area of the boiler, as well as in the cyclones after the boiler. This ash accounts generally for around 10–35% of the total amount of ash.
- Fly ash. This ash fraction is generated within a bag house filter and/or an electrostatic precipitator. Additionally or alternatively, fly ash can be produced as condensate sludge in flue gas condensation units. In case of combustion plants without such kind of flue gas cleaning, this ash fraction is emitted as residual dust via the chimney into the atmosphere. Usually the fly ash is the smallest portion of the total amount of ash and totals to 2–10% of the total ash amount.

Ash Characteristics In very general terms, the inorganic materials within most solid fuels, including biomass, can be divided into two broad categories:

- (a) The inherent inorganic material exists as part of the organic structure of the fuel. It is most commonly associated with oxygen-, sulfur-, and nitrogen-containing functional groups. These fundamental groups can provide suitable sites for the inorganic species to be associated chemically in the form of cations or chelates. Biomass materials tend to be relatively rich in oxygen-containing sites.

Thus a significant fraction of the inorganic material in most biomass fuels is in this form. For some inorganic species, it is also possible to be present in very fine particulate form within the organic structure of the fuels, and to behave essentially as an inherent component of the fuel.

- (b) Extraneous inorganic materials have been added to the fuel through geological processes or during harvesting, handling, and processing. Biomass fuels, for instance, are commonly contaminated with soil and other materials, which have become mixed with the fuel during collection, handling, and storage.

A listing of the major inorganic species found in the higher plants, and hence in the inherent inorganic material in most biomass materials, is given in Table 3. These data provide a rough quantitative overview of the major element speciation in biomass, divided into different categories.

The table makes it obvious that much of the inherent inorganic material in biomass is in the form of simple inorganic salts, and principally as the oxides and hydroxides of silicon, and the nitrates, sulfates, chlorides, phosphates, and oxalates of the alkali and alkaline earth metals. Table 3 shows further that a significant fraction of the inorganic material, in particular of the alkali metals, occurs in a water-soluble form.

The extraneous inorganic material can be in many forms. In most cases, however, it takes the form of contamination with sand, soil, or other mineral materials, tramp metal components, etc.

Ash Behavior There are inorganic constituents of biomass materials that are volatile at combustion temperatures, particularly some of the alkali metal (K and Na) compounds, the phosphates, and some of the heavy-metals species. These species might be released into the flue gases in the form of fume or as condensable vapor. Other inorganic species, principally the compounds of calcium and silicon, can be released from the burning fuel particle as very finely divided, submicron particles.

The balance of the inorganic fraction of the biomass will undergo a number of chemical and physical transformations, depending on the chemical composition, combustion temperature, and residence time, to form the larger residual ash particles.

Biomass Combustion for Electricity Generation. Table 3 Speciation of inorganic materials in higher plants, according to the classes “water soluble,” “organically associated,” and “precipitated” [12]

Element	Compound	Formula	Share of total element
<i>Class 1 – water soluble (free ionic form)</i>			
Na	Sodium nitrate, chloride	NaNO_3 , NaCl	>90%
K	Potassium nitrate, chloride	KNO_3 , KCl	>90%
Ca	Calcium nitrate, chloride, phosphate	$\text{Ca}(\text{NO}_3)_2$, CaCl_2 , $\text{Ca}_3(\text{PO})_4$	20–60%
Mg	Magnesium nitrate, chloride, phosphate	$\text{Mg}(\text{NO}_3)_2$, MgCl_2 , $\text{Mg}_3(\text{PO}_4)_2$	60–90%
Si	Silicon hydroxide	$\text{Si}(\text{OH})_4$	<5%
S	Sulfate ion	SO_4^{2-}	>90%*
P	Phosphate ion	PO_4^{3-}	>80%*
Cl	Chloride ion	Cl^-	>90%*
<i>Class 2 – organically associated (covalent)</i>			
Ca	Calcium pectate	Macromolecule	0.8–2.6%
Mg	Chlorophyll, magnesium pectate	$\text{C}_{55}\text{H}_{72}\text{MgN}_4\text{O}_5$, macromolecule-	8–35%
Mn	Various organic structures	Mn^{2+} , Mn^{3+} , Mn^{4+}	>80%*
Fe	Organic complex, organic sulfates	Fe^{3+} , Fe^{2+}	>90%*
S	Sulfolipids, amino acids, proteins	SO_4^{2-} , S	–
P	Nucleic acids	PO_4^{3-}	–
<i>Class 3 – precipitated (pure compound, amorphous, or crystalline)</i>			
Ca	Calcium oxalate	$\text{CaC}_2\text{O}_4 \cdot n\text{H}_2\text{O}$	30–85%
Fe	Phytoferritin	$(\text{FeO} \cdot \text{OH})_8 \cdot (\text{FeO} \cdot \text{OPO}_3\text{H}_2)$	Up to 50% in leaf tissue
P	Phytates	Ca-Mg-(K)-salt of $\text{C}_6\text{H}_6[\text{OPO}(\text{OH})_2]_6$	Up to 50–86% in seeds
Si	Phytolyte	$\text{SiO}_2 \cdot n\text{H}_2\text{O}$	

For items marked * no quantities have been reported. The value quoted indicates that the speciation is dominant one for that element

The key mineral transformations and chemical reactions that may occur at elevated temperature include:

- The fusion or partial fusion of quartz and silica particles and, at high temperatures, chemical interactions with other ash components, principally to form alkali and alkaline earth metal silicates
- The fusion or partial fusion of alumina-silicates
- The decomposition of carbonates, oxalates, chlorides, etc., and other inorganic salts
- The volatilization of alkali metals and some heavy metals
- Particle fragmentation by thermal shock and the rapid release of gaseous species from particles
- The coalescence of intra-particle mineral particles

The specific details of the release mechanism and residual ash formation processes depend largely on the type of combustor, i.e., on the flame temperature and the residence times at elevated temperatures.

Of relevance to the ash behavior at elevated temperatures is particularly the type of combustion technology, since the combustion conditions tend to be significantly different. For the three main different types (grate firing, fluidized bed combustors, and

pulverized fuel combustion systems) this is described below.

Grate-Fired Combustors In grate-fired systems, the fuel particles are distributed over a moving or static grate to form a fuel bed, with some of the combustion air being supplied from underneath. The normal intention is to retain the majority of the ash on the grate to be removed either manually or mechanically to an ash pit. Nevertheless a significant quantity of the ash will be released from the bed as fly-ash particles entrained in the combustion gases or in the form of vapors and fine fumes.

The maximum fuel bed temperatures in grate combustion of biomass materials are generally between 1,000°C and 2,000°C. The overall residence times on the grate are relatively long; they are commonly in the range of several minutes.

Depending on the chemical composition of the ash and the local bed temperature, a degree of sintering or fusion of the bed particles may occur. If the degree of fusion is excessive, relatively large ash agglomerates may be formed. This can interfere with the distribution of air through the fuel, and may affect the burnout of the char. The bed ash composition is usually fairly similar to that of the laboratory-prepared fuel ash, although it can sometimes be depleted in the more volatile inorganic species, principally potassium.

The coarse fly-ash particles are small particles of ash of up to an aerodynamic diameter of some 200–500 μm . They are entrained with the upward flow of under-grate air and the combustion gases, and are carried upward through the combustion room and the steam generator (i.e., heat exchanger). The chemical composition of the coarse fly ash is normally similar to that of the bed ash. There is commonly condensation of volatile inorganic species, particularly alkali metal sulfates, and some heavy-metal compounds, on the surface of the coarse fly-ash particles.

The fine aerosols generally within the submicron area are generated by condensation of the volatile inorganic species from the vapor phase (i.e., the alkali metal and some heavy-metal compounds) mostly as chlorides and sulfates. This happens as the flue gas cools down by passing through the boiler.

With regard to fly ash and aerosol generation from the grate combustion of woody biomass the following needs to be considered:

- The particle size distributions of the fly ashes are commonly bimodal. The main coarse fly-ash peak is in the range larger than 1 μm with a maximum particle size up to 500 μm and with the aerosol peak in the submicron range.
- The total fly-ash concentration in the flue gas is dominated by the generation of the coarse fly ashes by bed ash particle entrainment in the combustion gases. The quantity of fly ash is influenced by the ash content of the fuel and the grate operating parameters.
- The aerosol concentration in the flue gas and the composition of the aerosol material are influenced mainly by the chemical composition of the fuel (i.e., by the levels of volatile species (alkali metals, lead, and zinc) and of the very fine calcium-rich particulate material contained in the fuel).

Fluidized Bed Combustors In fluidized bed combustion systems, the fuel particles are suspended in a fluidizing air stream, along with a relatively coarse-grained bed material. The great majority of the ash leaves the fluidized bed combustors in the form of fly ash particles, generally of up to around 50–100 μm in diameter. This material also contains fine particles of elutriated bed material, which is commonly quartz, or unreacted limestone, with lime and calcium sulfate/sulfite.

The combustion temperatures that apply in fluidized beds are somewhat lower than those that apply in fixed beds. The bed and freeboard temperatures when burning biomass materials tend to be less than 900°C, and the ash particles tend, in a number of ways, to resemble the ash produced by combustion of the fuel in a laboratory furnace at similar temperatures.

In most fluidized bed combustion systems, the fuel ash and bed material particles tend to sinter and form agglomerates. The avoidance of this is an important combustor design and operational issue. Excessive agglomeration of the bed particles can lead to poor air distribution and eventually defluidization of the bed. In extreme cases, it may be necessary for the

operator to bring the combustor off line to remove and replace the bed material.

The bed ash sintering process involves the formation of particle-to-particle bonds, commonly by a viscous flow sintering mechanism, involving the low melting temperature ash components, initially in the form of necks between the particles. The key processes responsible for the formation of bonds between the bed particles in biomass-fired fluidized bed combustion systems are:

- Partial melting of the low melting point ash components to form a liquid phase of low viscosity, which, in turn, forms the necks between the bed particle.
- In some cases, the solid ash and bed particles, and particularly silicates and alumina-silicates species may be partially soluble in the liquid phase at the sintering temperature, and this can contribute to the strength of the particle-particle bonding. At higher bed temperatures, it is possible for a silicate melt of high viscosity to form on the surfaces of the bed material. The viscous liquid phase can also flow to form necks between the ash and bed particle.
- It is also possible for chemical reactions to occur at the surfaces of the bed particles, which can increase the strength of inter-particle bonds. The fact that lime on the surface of the bed particles reacts with SO_2 to form calcium sulfate is considered responsible for the sintering of bed particles in fluidized bed combustors firing high calcium biomass material [6].

Pulverized Fuel Combustors In pulverized fuel combustors, wherein biomass is usually fired together with coal since these are usually large-scale systems, the peak flame temperatures are very high compared to those of most other combustion systems. They are commonly around $1,600^\circ\text{C}$. The residence times at these temperatures are relatively short; they are in the order of a few seconds. The basic concerns in this case are with the behavior of the inorganic materials associated with the biomass when exposed to these very high temperatures and the conditions that apply in suspension flames. Another concern is the impact of the co-firing of the biomass on the behavior of the resulting ash (i.e., the mixed biomass-cal ash).

In general, the products of combustion of biomass materials when co-fired with coal in large-scale power plants show a higher level of submicron fume and vapor. Additionally the fly-ash particles tend to be significantly smaller than those formed by the combustion of pulverized coal.

The key ash-related impacts of the co-firing of biomass with coal are potentially on the slugging and fouling deposit formation potential of the mixed biomass-coal ash, and on the efficiency of the installed particulate collection equipment. Even biomass materials tend to have a relatively low ash content compared to most coals, the biomass ash materials tend to be relatively rich in alkali and alkaline earth metals, and these are effective fluxes for the alumina-silicate coal ashes. Therefore, the co-firing of biomass with coal will tend to increase both the slugging and fouling propensity of the mixed fuel, depending on the chemistry of the coal and biomass ashes and the co-firing ratio. At low co-firing ratios (i.e., less than about 10% on a mass basis) plant experience has indicated that these effects tend to be modest.

Ash Utilization For utilization and disposal of ash, the following possibilities are available:

- Industrial utilization (e.g., as additional component or raw material for cement, as chemical raw material, as additive in the metallurgical industry)
- Utilization in road construction
- Application as secondary feedstock with fertilizing and soil improving impact in the agriculture and forestry industry
- Dumping

Below different possibilities are discussed.

Industrial Utilization An industrial utilization of ash from biomass power plants may only be applied if a reasonable amount of ash with equal quality over time is available. In most cases, wood firing systems have only small throughput capacity and therefore produce not a sufficient amount of ash. For this reason an industrial utilization of ash from biomass is for the time being of academic interest only.

Utilization in Road Construction Slacking grate ash may be utilized in road construction, e.g., as replacement for gravel. This is only possible if

biomass fuel is used, which has not been chemically treated. Then the latent-hydraulically characteristics of wood ash is of advantage, since they contribute to a good setting of the humid material in the ground. In case of burning bark, e.g., the crude fraction of the grate ash is sieved and used in road construction. The fine fraction of the grate ash as well as the fine fly ash are usually not recommended to be used for that due to their high content of heavy metal and the higher amount of water-soluble components.

Utilization as Fertilizer and Soil Improving Material The following considerations can be made with regard to using ash as a fertilizer and soil improving material in agriculture and forestry:

- A mixture of crude ash and cyclone ash in plant-specific amount relations should be brought back to the area the biomass comes from in order to close the mineral and nutrient cycle as much as possible.
- The fine fly ash, being the smallest ash fraction, but shows the richest part of heavy metal, has to be dumped. This is valid also for ashes from the cleaning of heat exchangers of boilers and chimneys of small plants.
- The separation between multi cyclone and fly-ash stripper is the most efficient. However, this means that the biomass combustion plant has to have a fly-ash separation unit and this has to be located behind the multi cyclone. Otherwise a separation of this fraction is not possible.
- Ashes from plants firing waste wood usually cannot be brought to agricultural or forestry areas without prior treatment, since they are usually contaminated with heavy metals.
- Ashes from industrial residual wood combustion plants have an intermediate position between ashes from waste wood and ashes from natural wood with regard to their composition and amount of heavy metals. It depends to which extent the industrial wood has been contaminated in order to decide which measures and utilization options can be chosen.

In order to allow an unproblematic utilization, the ash has to be provided to the farmer in a suitable form:

- The ash fractions crude ash and cyclone ash have to be mixed according to the relation they are

produced. By this means a so called ash mixture after the ash formation is being created. The fly ash has to be collected separately and to be dumped according in accordance with the legal framework.

- The ash has to be provided in a condition that it can be strewed. This means it has to be free from slacking and stony parts with corn sizes above 1.5–2 cm.
- Iron parts, which are eventually in the ash (wires, nails, etc.), have to be removed as well. This can be done by means of permanent magnets.
- In a biomass power plant an automatic ash removal is recommended and usually standard. In case the bark portion inside the biomass fuel is more than 30%, an additional ash treatment (sieving or grinding) is required, since the slacking portion inside the ash is higher due to the mineral contamination in the bark (e.g., sand, soil, stones). Also for straw and cereal firing slacking is more common due to lower ash melting point and therefore such ash need to be treated similarly.

Biomass ash can be spread on land in a direct and an indirect way.

- Suitable for a direct spreading of ashes on agricultural areas and meadows are fertilizer caster with dust skirting. They allow a low cost, time saving, consistent, and mainly dust free distribution of the ash. For bringing the ash into the forest blowing machines are most suitable. They blow the ash from forest roads into the woods up to a distance of around 50 m.
- Alternatively the ash can also be used as additive in the agricultural composting. The advantage is that such an ash utilization can be performed almost dust free and that during the composting process also slacking and stone parts inside the ash do not negatively affect as they can be crushed inside the compost or sorted out during the resetting of the compost.

To avoid ecological negative impacts caused by ash spreading on soil, the following aspects should be considered.

- Only ash of chemically non treated biomass should be spread.
- Cyclone and fly ash must be collected separately and the fly ash should be dumped orderly.

- The usable part of the ash must be analyzed prior to the first spreading with regard to its nutrient and heavy metal content; such analysis must be repeated regularly according to the legal rules.
- For the usable portion from bark, wood chips, and shaving ash, the maximum amounts which should be spread on agricultural land shall be not more than 1,000 kg/(ha a), for grass land not more than 750 kg/(ha a) and not less than 3,000 kg/ha one time in 50 years [8]. In case the heavy metal fraction inside the ash is lower as the legally approved limits, the amounts given above can be increased.
- For the usable portion of the straw and cereal ash the amount of spreading has to be adjusted according to the nutrient needs of the respective plant culture.

Overall Energy Conversion Chain: Losses

Each energy conversion step is associated with losses and a certain “conversion step efficiency.” As a result, only a fraction of the energy fed as biomass into the biomass combustion to electricity generation facility can finally be fed into the grid as end energy (electricity) or used as heat.

A typical facility often used in Europe burns solid woody biomass on a grate or in a fluidized bed and

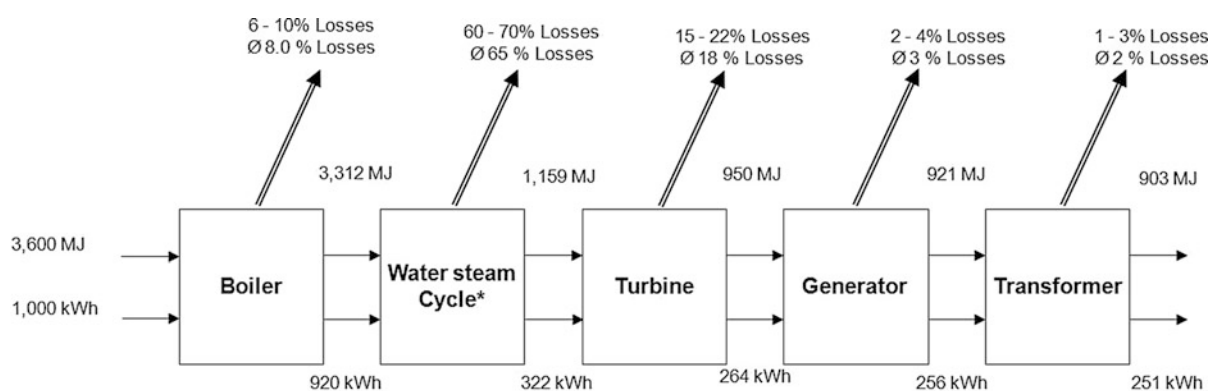
generates electricity out of this. Very often they are realized within an electrical power range between 5 and 20 MW_{el}. For such kind of standard application, Fig. 7 shows the energy flow and the average range of losses for each major conversion step. According to this out of 1,000 kWh (3,600 MJ) of biomass fuel such a standard plant can finally generate in the average around 251 kWh (903 MJ) of electricity. The biggest losses are within the water-steam cycle with 60–70% and within the turbine with 15–22%. Thus, the overall efficiency of such plant configuration ranges around 25%.

Environmental Impacts

Although biomass-to-electricity is a form of renewable energy generation, it is characterized by a number of environmental impacts. Most substantially are hereby the gaseous emissions, which are emitted via the chimney into the atmosphere.

Gaseous Emissions

There are a great number of different types of gaseous emissions from biomass power plants. They and their potential impact on environment, climate, and health are described in Table 4.



* remark: water steam cycle: including all energy losses in the water steam cycle, particularly condenser losses, except turbine and boiler losses

Biomass Combustion for Electricity Generation. Figure 7

Energy conversion chain of a typical biomass combustion facility for electricity generation in the range of 5–20 MW electricity (MJ and kWh values are calculated with the average loss figures)

Biomass Combustion for Electricity Generation. Table 4 Pollutants from biomass combustion and their impacts on climate, environment, and health [14]

Component	Biomass sources	Climate, environmental, and health impacts
Carbon dioxide (CO ₂)	Major combustion product from all biomass fuels	<i>Climate:</i> Direct greenhouse gas. However, CO ₂ emissions from biomass combustion are regarded as being CO ₂ -neutral with respect to the greenhouse gas effect ^a since biomass is a renewable fuel (if sustainably cultivated). (see also section “ The Greenhouse Gas Balance ”)
Carbon monoxide (CO)	Incomplete combustion of all biomass fuels	<i>Climate:</i> Indirect greenhouse gas through O ₃ formation <i>Health:</i> Reduced oxygen uptake especially influences people with asthma, and embryos. Suffocation in extreme cases
Methane (CH ₄)	Incomplete combustion of all biomass fuels	<i>Climate:</i> Direct greenhouse gas. Indirect greenhouse gas through O ₃ formation
Non Methane Volatile Organic Components (NMVOC)	Incomplete combustion of all biomass fuels	<i>Climate:</i> Indirect greenhouse gas through O ₃ formation <i>Health:</i> Negative effect on the human respiratory system
Polycyclic Aromatic Hydrocarbons (PAH)	Incomplete combustion of all biomass fuels	<i>Environment:</i> Smog formation <i>Health:</i> Carcinogenic effects
Particles	Soot, char and condensed heavy hydrocarbons (tar) from incomplete combustion of all biomass fuels. Fly ash and salts	<i>Climate and environment:</i> Reversed greenhouse effect through aerosol formation. Indirect effects of heavy-metal concentrations in deposited particles <i>Health:</i> Negative effect on the human respiratory system. Carcinogenic effects
Nitrogen oxides (NO _x , (NO, NO ₂))	Minor combustion product from all biomass fuels containing nitrogen. Additional NO _x may be formed from nitrogen in the air under certain conditions	<i>Climate and environment:</i> Indirect greenhouse gas through O ₃ formation. Reversed greenhouse effect through aerosol formation. Acid precipitation. Vegetation damage. Smog formation. Corrosion and material damage <i>Health:</i> Negative effect on the human respiratory system. NO ₂ is toxic
Nitrous oxide (N ₂ O)	Minor combustion product from all biomass fuels containing nitrogen	<i>Climate:</i> Direct greenhouse gas <i>Health:</i> Indirect effect through O ₃ depletion in the stratosphere ^b
Ammonia (NH ₃)	Small amounts may be emitted as a result of incomplete conversion of NH ₃ , formed from pyrolysis/gasification, to oxidized nitrogen-containing components. Secondary NO _x reduction measures by NH ₃ injection (SNCR, SCR)	<i>Environment:</i> Acid precipitation. Vegetation damage. Corrosion and material damage <i>Health:</i> Negative effect on the human respiratory system
Sulfur oxides (SO _x (SO ₂ , SO ₃))	Minor combustion product from all biomass fuels containing Sulfur	<i>Climate and environment:</i> Reversed greenhouse gas effect through aerosol formation. Acid precipitation. ^c Vegetation damage. Smog formation. Corrosion and material damage <i>Health:</i> Negative effect on the human respiratory system, asthmatic effect

Biomass Combustion for Electricity Generation. Table 4 (Continued)

Component	Biomass sources	Climate, environmental, and health impacts
Heavy metals	All biomass fuels contain heavy metals to some degree, which will remain in the ash or evaporate	<i>Health:</i> Accumulate in the food chain. Some are toxic and some have carcinogenic effects
(Ground level) Ozone (O ₃)	Secondary combustion product formed from atmospheric reactions including CO, CH ₄ , NMVOC and NO _x	<i>Climate and environment:</i> Direct greenhouse gas. Vegetation damage. Smog formation. Material damage
		<i>Health:</i> Indirect effect through O ₃ depletion in the stratosphere. ^b Negative effect on the human respiratory system, asthmatic effect
Hydrogen chloride (HCl)	Minor combustion product from all biomass fuels containing chlorine	<i>Environment:</i> Acid precipitation. Vegetation damage. Corrosion and material damage
		<i>Health:</i> Negative effect on the human respiratory system. Toxic
Dioxins and furans (PCDD/PCDF)	Small amounts may be emitted as a result of reactions including carbon, chlorine, and oxygen in the presence of catalysts (Cu)	<i>Health:</i> Highly toxic. Liver damage. Central nervous system damage. Reduced immunity defense. Accumulate in the food chain

^a*The greenhouse gas effect:* The natural greenhouse gas effect keeps the Earth's mean temperature at about 15°C. Without the greenhouse gas effect, the Earth's mean temperature would be -18°C. Anthropogenic sources of greenhouse gases are generally believed to contribute to an increasing greenhouse gas effect, causing the Earth's mean temperature slowly to increase. From 1750 to 1994, the concentration of the three most important greenhouse gases - CO₂, CH₄, and N₂O - increased by 30%, 145%, and 15%, respectively (contributing to an increasing greenhouse gas effect). However, particles, SO₂ and NO_x contribute, to some degree, to a reversed greenhouse gas effect caused by aerosol formation

^b*Depletion of the ozone layer:* The atmospheric ozone layer is found in the stratosphere, 10–40 km above ground level. Ozone absorbs ultraviolet radiation from the sun and prevents damaging radiation from reaching the Earth's surface. Ozone in the stratosphere may be reduced by reactions with NO, where NO may be formed from N₂O in a first reaction step. Ground level ozone, however, is a pollutant and a greenhouse gas

^c*Acid precipitation:* Emissions of NO_x, SO_x, and HCl result in acid precipitation through the formation of acids

The amount of emissions is usually given in mg/MJ fuel and these are dependent from a huge number of items. A very important one is certainly the type of technology used for combustion. The typical amount of emissions for different important combustion technologies are shown in Table 5.

These emissions can be reduced by primary measures and secondary measures. Secondary measures belong to the flue gas treatment facility and have already been described in section “[Flue Gas Treatment](#)”. The main primary emission control and reduction measures are described below.

Generally it can be stated that all emissions which are avoided by primary emission control and reduction measures do not need to be targeted by any secondary

emission control measure. Thus the usual way is to use as much as possible the primary emission control and reduction measures to limit the effort (investment and operating cost) for secondary emission reduction measures.

Primary emission reduction measures aim to prevent or reduce the formation of emissions and/or a reduction of emissions within the combustion chamber. Several possible measures exist. The most important with regard to the combustion of solid biomass are described below:

- Modification of the fuel composition. The concentration of K, Na, S, Cl, Zn, and Pb in the fuel determines the mass of aerosol emissions as well

Biomass Combustion for Electricity Generation. Table 5 Arithmetic average emission values from wood combustion applications [12]

	NO _x as NO ₂ (mg/MJ)	Particles (mg/MJ)	Tar (mg/MJ)	CO (mg/MJ)	UHC as CH ₄ (mg/MJ)	VOC (mg/MJ)	PAH (μg/MJ)
Fluidized bed boilers	170	2	n.m.	0	1	n.m.	4
Pulverized fuel burners	69	86	n.m.	164	8	n.m.	22
Grate plants	111	122	n.m.	1,846	67	n.m.	4,040

Data were collected from investigations in various IEA countries (Norway, Switzerland, Finland, the UK, and Denmark)
n.m. not measured, *UHC* unburned hydrocarbons

as their chemical composition. These elements can be removed from the fuel to a certain extent. A possible measure is fuel washing. For example, straw can be washed by leaving it on the field for some time after harvesting, exposing it to rain. Another possibility is a controlled washing. However, this may go along also with energy losses which might be counterbalanced by the positive effect on reduced emission control measures (and even a longer lifetime of the boiler).

- Modification of the moisture content of the fuel. High moisture content in the biomass fuel makes it difficult to achieve a sufficiently high temperature in the combustion chamber. However, high temperatures (above 850°C) are necessary to ensure a sufficiently low level of CO within the flue gas. Thus, due to incomplete combustion high emissions may be the result. Drying the fuel helps to solve this problem. Drying can be done naturally or artificial. Natural means, e.g., that the biomass is left at the atmosphere protected by rain and simply is getting dryer by time. With artificial drying, the water content can be reduced much further. However, if no waste heat without additional cost is available, artificial drying of biomass is much too costly. Therefore, mostly the biofuel is dried with solar energy.
- Modification of the particle size of the fuel. The size of the particles is important for the emissions to be produced for two reasons: The particle size defines very much the combustion technology selection. Technology selection has an impact on the amount of emissions produced. For a given or selected

technology, the size of particle can still vary and insufficient precise sizing may result in incomplete combustion. The consequences are a lower efficiency and higher emission.

- Selection of the type of combustion technology and the type of equipment. There are various reasons for choosing a certain combustion technology. Based on this decision the design of the other components is realized. One of the results of this technology selection is the amount of emissions produced during the combustion process. Substantial emission reduction can be achieved by selecting the best possible combustion technology for a given fuel and by optimizing the combustion process including primary reduction measures.
- Improved construction of the combustion application. In order to obtain a full combustion by minimizing emissions, (1) sufficiently high combustion temperatures, (2) sufficiently long residence time, and (3) optimal mixing of the fuel gas and air have to be ensured. These items are partly determined by the combustion technology and the design of the boiler and partly by the combustion process operation.
- Combustion process control optimization. A combustion control system aims to govern selected process parameters according to a predefined scheme. Whereas usually the primary goal of a process control device in a biomass combustion facility is to adjust the heat production in the boiler according to what is required (e.g., by the steam turbine), the process control unit can be also programmed for simultaneous optimization of the combustion

process with respect to minimize emissions and maximize thermal efficiency. An adequate combustion control system can substantially lower the emissions in the flue gas. Typical process parameters to be used as process control parameters are the concentration of CO, C_xH_y , and O_2 in the flue gas, the combustion chamber temperature, and the boiler temperature. Process variables directly adjusted to achieve the targets for the aforementioned process parameters are typically the amount of fuel fed into the boiler.

- **Staged-air combustion.** Staged-air combustion makes it possible to reduce simultaneously emissions from incomplete combustion and NO_x through a separation of devolatilization and gas phase combustion. This results in improved mixing of fuel gas and combustion air. In the first stage, primary air is added for devolatilization of the volatile fraction of the fuel, resulting in a flue gas consisting mainly of CO, H_2 , C_xH_y , H_2O , CO_2 , and N_2 . For NO_x -emission reduction, the fuel gas content of NH_3 , HCN, and NO is also of particular interest. In the second stage, sufficient secondary air is supplied to ensure a good burnout and low emission levels from incomplete combustion. An improved mixing of fuel gas and secondary air reduces the amount of secondary air needed. This results in higher flame temperatures and a lower overall excess air ratio. Hence, emissions from incomplete combustion are reduced by a temperature increase, which speeds up the elementary reaction rates, and by improved mixing, which reduces the residence time needed for mixing the fuel gas and the secondary combustion air. However, this does not mean that the NO_x -emission level is reduced automatically as well. An efficient reduction of emissions from incomplete combustion and NO_x emissions can only be achieved by optimization of the primary excess air ratio.
- **Staged fuel combustion and re-burning.** Staged fuel combustion and re-burning are other possibilities for NO_x reduction in biomass combustion applications. The primary fuel is combusted with an excess air ratio above 1, and no significant NO_x reduction occurs. Then a secondary fuel is injected into the flue gas after the primary combustion zone, without additional air supply. Based on this a sub-

stoichiometric reducing atmosphere is created in which NO_x formed in the primary zone may be reduced, by reacting with NH_3 and HCN formed from the secondary fuel (if the secondary fuel contains nitrogen) in a similar manner as for staged-air combustion. Additionally, NO is converted back to HCN by reactions with HCCO and CH_i radicals ($i = 0-3$) formed from the secondary fuel. This process is called re-burning. Under typical conditions, HCCO appears to be the most effective radical for removing NO. Finally, a sufficient amount of air is added after the reducing zone to achieve a good burnout with an overall excess air ratio above 1. Staged fuel combustion requires automatic feeding of the primary and secondary fuel, and the secondary fuel must be easily adjustable. This limits the use of stage fuel combustion to large-scale biomass combustion applications, since a suitable combustion process design with two fuel-feeding systems as well as an accurate combustion process control is necessary. Natural gas, fuel oil, pyrolysis gas, biomass powder, sawdust, or similar fuels can be used as secondary fuels.

- **Catalytic converters.** A catalytic converter consists of a durable, heat-resistant ceramic composition extruded into cellular or honeycomb configuration. After extrusion, this ceramic monolith is fired and then covered with a noble-metal catalyst (usually platinum, rhodium or palladium, or combinations of these) or metal oxides. It is of paramount importance that the catalyst has a high thermal stability and a good poison resistance to avoid its deactivation. Such catalytic converters are utilized to some degree in small-scale biomass combustion applications (e.g., wood-stoves) but rather seldom in biomass-to-electricity applications.

The Greenhouse Gas Balance

Special attention has to be given to the carbon emissions of biomass power plants. As every thermal power plant using carbon-based fuel (e.g., coal, gas, oil), a biomass power plant emits CO_2 into the atmosphere. It is therefore not CO_2 neutral. And due to the fact that typical biomass-to-electricity power plants have – mainly due to smaller electrical capacities – lower

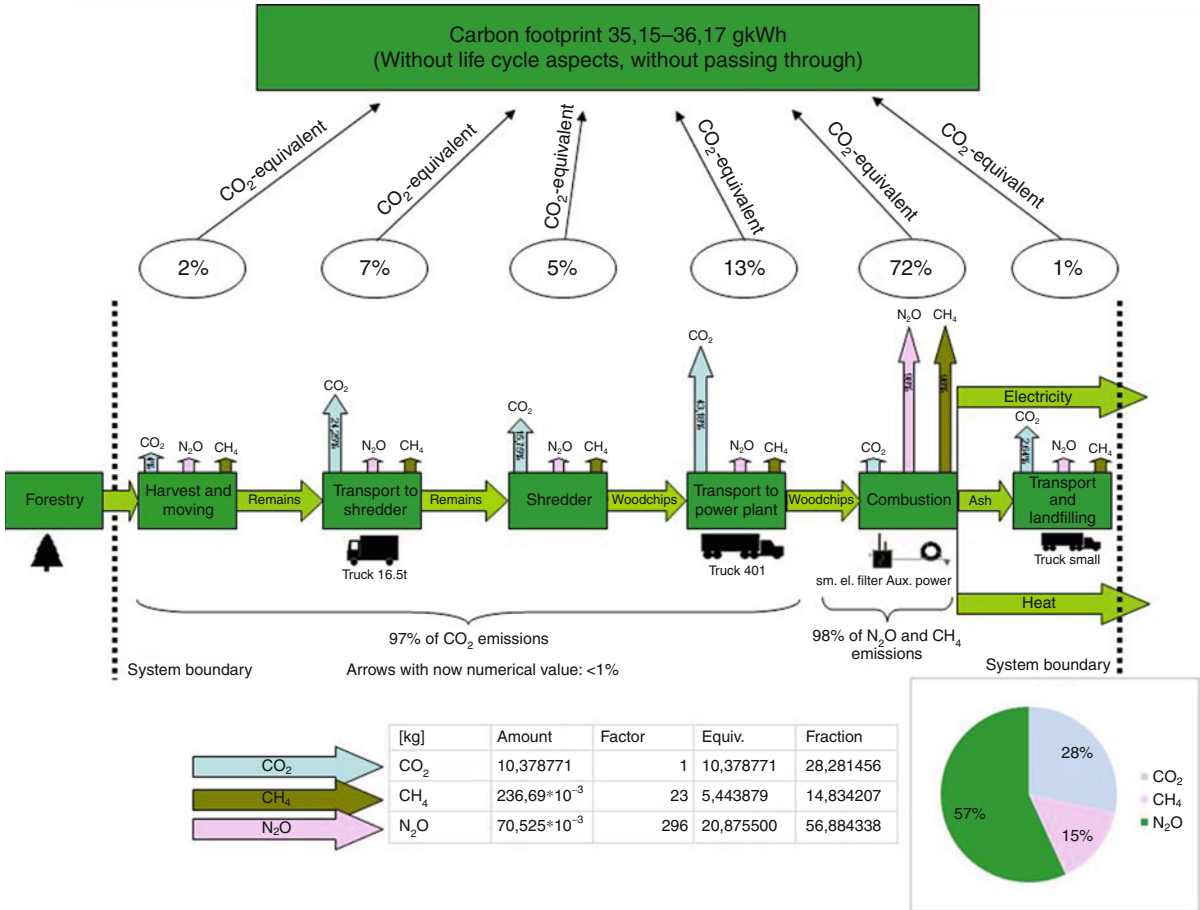
average efficiencies as, e.g., large-scale modern coal power plants, gas combined cycles or other types of fossil thermal power plants operated with fossil fuel energy, the direct emissions of a biomass power plant per unit of generated electricity are usually higher.

However, in order to assess the impact on the climate, and this is the main issue of the discussions about the pros and cons of CO₂ emissions, the entire life cycle of the biomass has to be considered. Assuming a sustainable biomass production, the same amount of CO₂, which is being emitted during combustion into the atmosphere, has been absorbed out of the atmosphere during the growing phase of the plants on the fields or in the forests. Thus, the assumption can be

made that electricity generation from sustainable produced biomass is climate neutral.

Nevertheless, this is not the full truth. In fact, to allow that the biomass can be converted to electricity, there are a number of energy conversion steps necessary, which either need additional auxiliary energy or where energy is getting lost (see section “Overall Energy Conversion Chain: Losses”). These losses respectively needs for auxiliary energy result all in climate gas emissions.

Figure 8 shows exemplarily for a biomass plant for electricity generation the conversion chain and the resulting portion of emissions in CO₂-equ./kWh_{el}. Overall the carbon footprint results in 35–36



Biomass Combustion for Electricity Generation. Figure 8

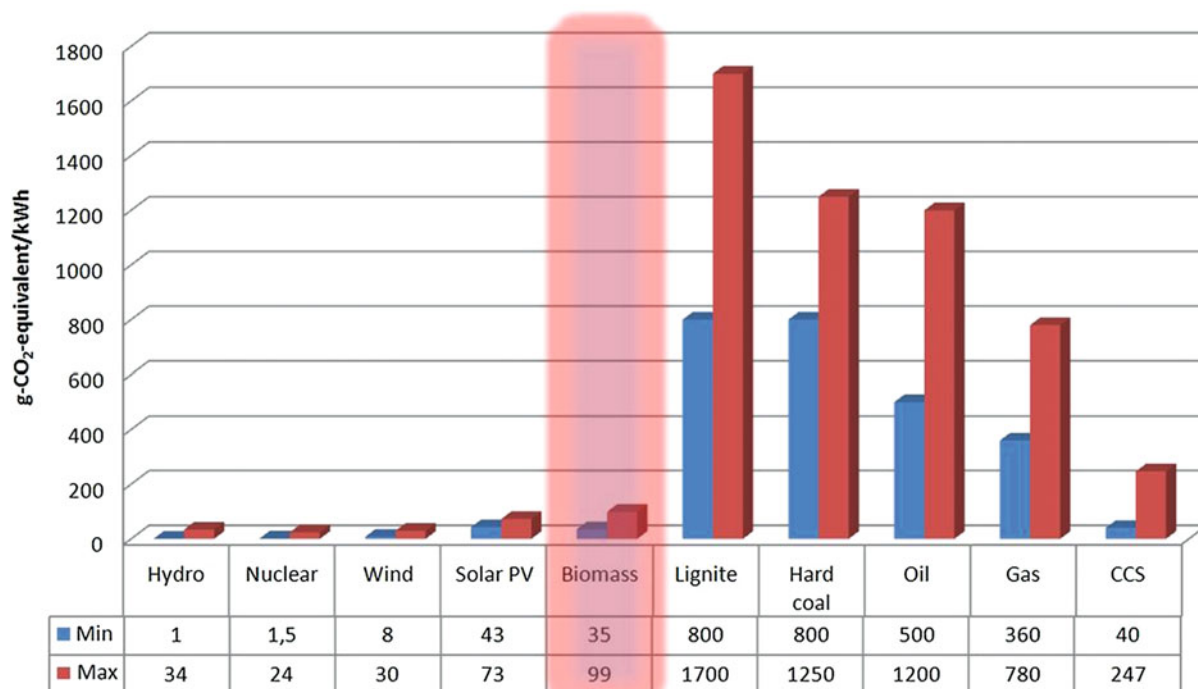
Carbon emissions at the example of a medium size biomass power plant (5 MW_{el}), 20% efficiency fired with residual forest wood [16]

CO₂-equ./kWh_{el}, whereby the carbon footprint is defined as the total set of greenhouse gases (GHG) emissions caused by a product during its lifetime [17]. For climate relevant gases other than CO₂ (e.g., methane, see also Table 4) their impact on climate is calculated relative to 1 ton of CO₂. This bandwidth does not include the CO₂ emissions due to combustion, which have been absorbed before by the photosynthesis from the atmosphere. Most of the carbon footprint in Fig. 8 is contributed during the combustion due to the emissions of CH₄ and N₂O [13, 16].

The greenhouse gas balance of biomass has to be compared with other forms of producing electricity in order to arrive at an overall judgment of the balance. Figure 9 therefore shows the average bandwidth of CO₂-equ.-emissions of different electricity generation options. According to this biomass is characterized by very low greenhouse gas emissions, being in the range of 35 to almost 100 gCO₂-equ./kWh_{el}. For example, for lignite the values are more than 10–20 times as high as

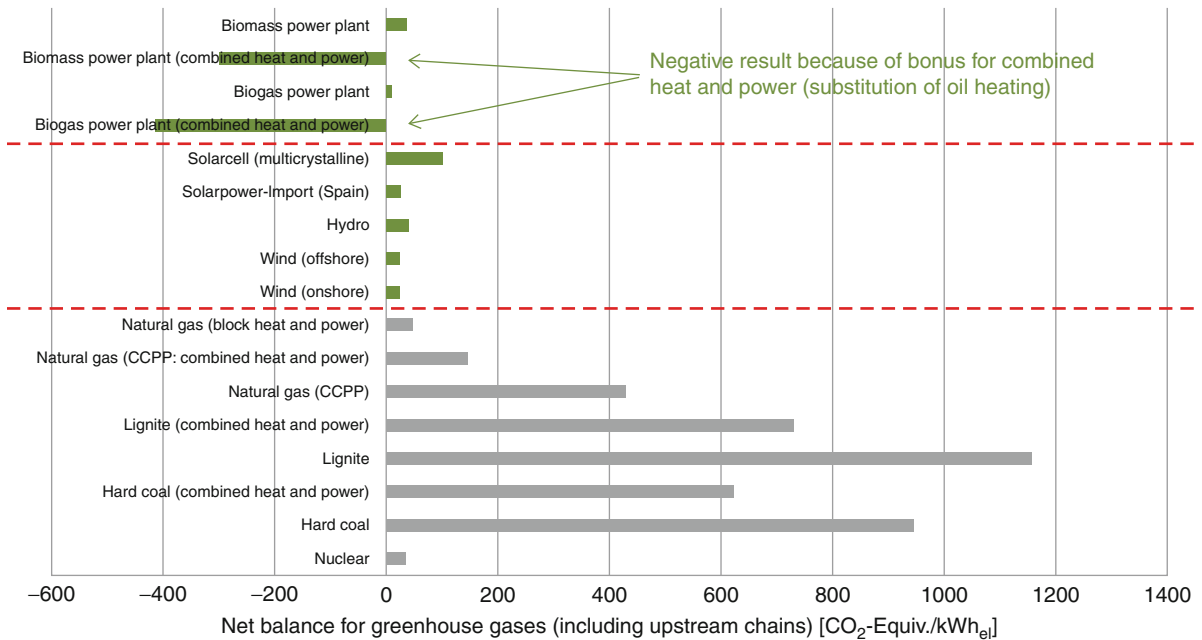
for biomass. Still for natural gas, which has a much less carbon content as coal and can be converted into electricity with a much higher efficiency, there is a factor of between 6 and 10 between these two technologies.

In case the electricity generation is combined with heat utilization (combined heat and power) and subject to the methodology, how the carbon emissions are distributed between the final end products electricity and heat, the greenhouse gas balance, or so to say the carbon footprint can become even negative. This can be seen in Fig. 10, wherein once again several technologies are compared based on special designed technology layouts and differentiated between pure electricity generation and combined heat and power. According to this, biomass- and biogas-combined heat and power options are the only technologies showing a negative carbon footprint, in case the emissions saved due to the replacement of heat from other conventional sources and their resulting CO₂ emissions are being subtracted from the carbon footprint of biomass or biogas.



Biomass Combustion for Electricity Generation. Figure 9

Life cycle emissions of selected electricity generation technologies [16]



Biomass Combustion for Electricity Generation. Figure 10

Net balances of carbon equivalent emissions of different power generation technologies with and without combined heat and power generation [16]

Other Environmental Impacts

Other environmental impacts that may occur with biomass-to-electricity-generation can be (1) emissions in liquid form into the ground, (2) smelling, (3) noise emissions, and (4) visual impacts. Smell usually is a result of any gaseous emissions and occur sometimes, e.g., from the fuel storage. The others (point (1), (3), and (4)) are usually at a low level, if the plant is well planned and designed and fulfills the respective local requirements.

Cost Analysis

As with all energy conversion technologies, it is differed generally also in biomass-to-electricity facilities between investment and O&M cost. The overall cost varies widely. Some of the most important dependency factors are:

- The type and quality of the fuel
- The combustion technology as well as the whole concept and design of the plant

- The capacity of the plant
- The country
- The location of the power plant (country, and the specific location inside the country)
- The available infrastructure at the site
- The available know-how to design, build, and operate the power plant

Investment Cost

Investment cost covers the cost for all equipment and services necessary prior to the commercial operation of the power plant: biomass preparation facility, biomass storage and handling facilities, the power plant itself, emission reduction devices, cooling devices, grid connection, water supply, waste water system, all other balance of plant components, concept and detailed engineering, all consultancy fees and financing cost.

The following Table 6 provides with an overview of typical ranges of specific investment cost for different but quite common types of biomass to electricity generation plants. As can be seen therein, the most

Biomass Combustion for Electricity Generation. Table 6 Overview of investment of biomass to electricity combustion facilities

	Biomass steam power plants	IGCCs with biomass	CHP engines	Biogas plant + engine	Steam engines	Stirling engines
Usual type of biomass fuel	Solid biomass	Biogas, wood gas	Biofuel, biogas, wood gas	Biogas	Solid biomass	Solid biomass
Typical plant size range	5–20 MW	10–50 MW	500 kW to several MW	100 kW to several MW	100 kW to several MW	<100 kW to 1 MW
Investment cost range in €/kW	3,000–5,000	4,000–7,000	1,000–2,000	3,000–5,000	4,000–6,000	up to 10,000

common type biomass steam power plants have investment cost usually in the range between 3,000 and 5,000 €/MW.

O&M Cost

O&M cost are the annual cost of the power plant and are differentiated between:

- Fuel cost, which are usually the most important cost component
- Cost for waste disposal (ash, waste from emission cleaning devices)
- Regular and irregular maintenance
- Auxiliary media (water, electricity, lubricants)
- Operation personnel cost (administration staff and monitoring personnel)
- Spare parts
- Insurances
- Land lease

The above mentioned cost can be divided into two main classes: those which are fixed (i.e., independent from the amount of electricity produced annually) and those which are variable (i.e., depend on the annual electricity generation). Fuel costs as well as cost for auxiliary media are typical variable costs, whereas cost for land lease, insurances, and part of the operation personnel costs are usual fixed costs.

The typical relation between the overall investment cost and the overall O&M cost during the life time of a project depends on the cost impact of each cost component, but mostly it is influenced by the fuel cost. An example the typical fuel cost of a waste wood burning biomass power plant in Germany are in the

range of 30–50 €/t. Taking 50 €/t as example and average energy efficiencies for a 20 MW-plant (i.e., base load plant) with 8,000 h/y of nominal load hours into account, the overall fuel cost over a 20 year life cycle of the plant is around 180 Mio. € (assuming additionally a calorific value of the biomass fuel of 16 MJ/kg). This is then double the amount of investment cost being between 80 and 100 Mio €. This example shows how important the fuel price, but also any measure to reduce the fuel consumption is (i.e., to increase conversion efficiency).

All other O&M cost are together substantially less than the fuel cost. For biomass power plants they are roughly in a range of around 4% of the total investment.

Example: Cost Analysis

A first indication of the financial feasibility of a biomass power plant can be derived by calculating the levelized electricity generation cost (LEC). They are calculated based on the annuity of the investment cost over the technical lifetime of the plant, adding to this the average annual O&M cost and dividing this through the average annual electricity generation. In case of combined heat and power production, the investment and O&M cost need to be divided to these two products, whereby different methods for such division exists.

For a standard example based on German frame conditions for purely electricity generation (i.e., no combined heat and power supply) and based on the technical and financial frame conditions as given in [Table 7](#), the levelized electricity generation cost are calculated hereunder. The results are given in the

Biomass Combustion for Electricity Generation. Table 7 Example calculation of the levelized electricity generation cost of biomass and biogas power plants in Germany, 2009 figures

		Case 1	Case 2
Installed capacity	MW	5	20
Full load hours	h/year	8,000	8,000
Annual electricity sales	MWh/year	40,000	160,000
Technical lifetime	Year	25	25
Total average efficiency	%	24	30
Total amount of fuel needed (in form of wood or biogas)	MWh/year	167,000	533,000
Specific investment	€/kW	3,000	2,600
Total investment cost	€	15,000,000	52,000,000
Specific O&M cost without fuel	€/kW year	300	113
Fuel cost incl. logistics	€/t	20	25
Fuel cost	€/kWh fuel	0.008	0.006
Fuel cost	€/year	1,340,000	3,000,000
Total O&M cost incl. fuel cost	€/year	2,840,000	5,250,000
Equity	%	20	20
Loan	%	80	80
Required RoE	%	12	12
Interest on loan	%	5	5
Average interest	%	6.4	6.4
Annuity	€/year	1,218,000	4,224,000
Total annual cost	€/year	4,058,000	9,474,000
Levelized Electr. Gen. Cost (LEC)	€/kWh	0.10	0.06

table below. Under these assumptions the levelized electricity generation cost are between 0.06 and 0.10 €/kWh for biomass power plants.

Future Perspectives

Due to high energy price levels and promising policy conditions electricity generation from biomass is increasing on a worldwide scale. This is especially true for industrialized countries. Table 8 summarizes the worldwide use of biomass for electricity generation as per status end of 2008. As one can see, in total an amount of 256–386 TWh/year of electricity has been generated globally in 2008 from biomass including also the biomass fraction of waste-to-energy plants. Around 90 TWh/year has been generated in the Europe.

Compared to the overall electricity generation from renewable energies, this is a share between 7% and almost 10%. Compared to the overall electricity generation worldwide in total (in 2008 estimated to be around 21,000 TWh/year), biomass contributes roughly around 1–2%.

With regard to the various submarkets, differentiated with regard to the fuel type/origin, the market consideration are as follows:

- **Solid fuel.** Currently, as end of 2008, at least 46 GW of solid biomass is utilized to produce electricity via mono- and co-combustion worldwide. The electrical power is installed equally in developing and industrial countries. With this installed capacity at an average of 4,000–7,000 of full load hours per year

Biomass Combustion for Electricity Generation.**Table 8** Electricity generation from biomass worldwide and in the EU-countries (status end of 2008) [9]

	Installed capacity in GW ^a		Electricity generation in TWh/a ^a	
	World	EU 27	World	EU 27
Solid Biomass	46	10	(190–320)	50
Municipal solid waste ^b	n.a	n.a	29	15
Biogas	>6	6	37 ^c	25 ^c
Total Biomass	52	16	256–386	90

^aAs far as statistical data available, values in brackets are estimated^bOnly OECD countries^cIncluding the use of liquid biofuels

between 180 and 320 TWh of electricity can be produced. About 40% of the total electricity generated by solid biomass in the OECD countries has been realized within the European Union. There, the main producers are the three densely wooded countries Finland, Germany, and Sweden, producing more than half of the electricity generated by solid biomass in the EU. In many countries the energy recovery of municipal solid waste is counted to solid biomass. In the OECD about 29 TWh of electricity is estimated for 2008 assuming a similar increase as in 2007. Considering the measures taken to protect the world's climate a further growth of the power production from solid biomass is to be expected in the years to come. The growth will be very much influenced by the price level of the biomass materials which itself is strongly influenced by the fossil fuel price levels.

- **Biogas.** The electricity generation from biogas mainly takes place in industrialized nations. Considering the around 29 TWh of electricity from biogas, which has been generated in OECD countries in 2007, a total of roughly 32 TWh can be estimated for 2008. The main contribution comes from the EU. Global players on the biogas market are Germany (9–10 TWh) and the United Kingdom (5–6 TWh). Nearly half of the biogas in the EU is generated by landfills, of which almost half is produced in the United Kingdom. The remaining

biogas is produced by agricultural biogas power plants, using mainly liquid and solid manure and maize, and by sewage gas power plants.

- **Liquid fuels.** Only a small part of liquid fuels is used for electricity generation globally. However, this use is statistically recorded in very few industrial nations only. Compared with the prior years, the use of liquid fuels for electricity generation in combined heat and power plants has stagnated or decreased in selected countries in 2008.

The worldwide electricity generation from biomass is characterized by a large spectrum of available technologies. The technologies used in developing countries show on average very low efficiencies and rather high emissions. In contrast, in industrialized countries more innovative technologies with significantly higher efficiencies and rather lower airborne emissions are applied. The longest history and best knowledge exists with the use of woody biomass. Due to its favorable fuel properties large quantities can be easily stored. Moreover, the used combustion and power generation techniques are upgraded technologies of the coal firing industry. Other technology trends are a further increase of the efficiency, e.g., by minimizing heat losses and utilizing heat recovery from exhaust gases, by increasing the conversion rates (on a lower temperature level), and the development of interim storage capacities for a more flexible energy supply. Such technologies are in place next to the generally known steam turbines and Stirling engines as well as complex concepts like the Organic-Rankine-Cycle (ORC) and Kalina-Cycle process. Furthermore, due to the strongly varying price level of fossil fuels and the growing competition on reasonably priced biofuels, the use of a wide range of solid biomass residues from industry, forestry, and agriculture as well as the use of energy crops becomes more prominent. Thus, R&D moves toward the development of new and more specialized technologies able to accept unfavorable fuel properties like high concentrations of nitrogen, potassium, or sulfur. Furthermore, fuel and logistic concepts based on the use of compacted biofuels with high energy densities (like briquettes and pellets including pellets from torrefied biomass) will be more and more interesting in the future and can improve the total efficiency and economy of energy supply concepts.

Abbreviations

BoP	Balance of plant
CHP	Combined heat and power plant
GCV	Gross calorific value
GHG	Greenhouse gases
LEC	Levelized electricity generation costs
NCV	Net calorific value
ORC	Organic Rankine Cycle
SCR	Selective catalytic reduction
SNCR	Selective non-catalytic reduction

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Biomass Crops for Biofuels and Bio-based Products

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Article Outline

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Glossary

Agriculturally marginal land Land that is not arable without compromising soil stability and increasing salinity. It requires large number of inputs.

Bio-based products Products derived from biological sources as opposed to oil.

Bioenergy Energy derived from biological, renewable sources – not from petroleum.

Biofuel Fuels derived from biological sources.

Biomass Materials derived from plant or animal origin, i.e., dedicated agriculture, agricultural residues, municipal waste, and forestry.

Corn stover The remaining stalks and leaves of the corn plant after the grain has been removed.

Dedicated energy crops Crops grown only for use in the biofuels industry, e.g., switchgrass and *Miscanthus*, poplar and *Eucalyptus*.

Herbaceous Plant materials that have green, nonwoody above-ground parts rather than lignified stems and those parts generally die at the end of the growing season.

Lignocellulose Cell wall materials from plants that contain cellulose, hemicellulose, and lignin.

Megagram (Mg) A unit of mass equal to 1,000,000 g. Also referred to as a metric ton (US)

Perennial Plants that persist for multiple years and often have woody stems.

Renewable resources Materials and products derived from plants that are generated through growth using energy from sunlight and nutrients from soil.

Sustainable Materials that can be maintained through inputs that are equal or less than harvested output.

Water use efficiency The amount of biomass produced from photosynthesis compared to the amount of water taken up by the plant. C4 plants are more efficient in photosynthetic sugar production per CO₂ taken in, thus lowering the amount of water required to obtain the CO₂ and thus the sugars.

Definition of the Subject and Its Importance

Humans currently consume at least 25% more raw materials every year than are replaced through biological growth [150]. In order to sustain quality of life and have adequate environmental resources, those resources must be balanced and renewable. Pressure on those resources has never been greater with the world population nearing seven billion people, and estimated to plateau at 10.5 billion by 2050. That number represents 35–40% more people than currently inhabit the earth.

Sustainable, renewable resources are those derived from biological sources, primarily plant biomass. The underlying principal is that the materials can be reproduced with minimal inputs using energy from

the sun. Biomass is thus derived directly or indirectly from original sources that grow and reproduce biologically.

Biomass for biofuels and bio-based products can include many sources of material. In general, biomass includes any biological materials whether of plant or animal origin: agricultural harvests such as grains, agricultural residues such as stalks and leaves, perennial crops such as hay and trees, animal manures, building waste wood, municipal solid waste such as paper, and various food industry wastes.

Introduction

The heavy reliance of the western economies on fossil fuels has given rise to energy security concerns. These concerns taken together with the sustainability issue, negative environmental impacts, and the rising cost of petroleum fuel have prompted the development of viable alternatives that are sustainable, cleaner, and environmentally neutral. Biofuels, which have emerged as one of the alternatives to address these concerns, are obtained from renewable biomass which represents a key long-term component of a sustainable biofuels industry. Ethanol from corn is the first-generation biofuel produced in USA and Europe. However, corn ethanol alone will not be sufficient to address the nation's energy needs. Cellulosic ethanol from renewable resources such as forest and agricultural biomass must also be considered. The "Billion Ton Study" supported by the US Department of Energy (DOE) and US Department of Agriculture (USDA) estimated that renewable resources are available from forest and agricultural lands to produce enough cellulosic ethanol to displace 30% or more of transportation fuel needs annually [1]. This will significantly reduce the country's dependence on imported oil.

This review deals only with plant-based crops that are used as biomass sources. Crop categories discussed include agricultural residues, dedicated woody crops – poplar and *Eucalyptus*, perennial herbaceous grasses – *Miscanthus* and switchgrass, and grass species that produce soluble sugar streams – sweet sorghum and sugarcane. Although many other crop sources are generally considered as potential sources of biomass, these are the front line crops that are considered to be "near term" candidates.

Agricultural Residues for Bioenergy

Availability of Feedstock

The Billion Ton Study on biomass estimated that 388 megagrams (Mg) of agricultural postharvest residues per year could be available from agriculture for conversion to energy resources in the USA within the next 20 years [1]. The estimated crop residues were primarily from corn stover, wheat straw, rice straw, and hulls as well as other crops with lesser individual contributions. The estimated amount of ethanol that can be derived from crop residues totals 138 billion liters assuming 356 L Mg⁻¹ (85 gal t⁻¹). Additionally, the study made the assumptions to support three different scenarios for productivity. The first scenario was to maintain the status quo for all resources available today, and those would be available at the same level in the future. The second scenario focused on technology changes being applied to current crops to generate higher yields. The third and most lucrative scenario assumed that the technology changes would be applied to current crops as well as new perennial crops, combined with significant land use changes. The 388 Mg estimate is based on the third scenario.

One of the major contributors to crop residue potential in the USA is corn stover, whether under current production or assuming increased crop yields [1]. Stover can be used for many bio-based products, and the use of corn stover for those products would remove it from its contribution to liquid transportation fuels. Some of these current and potential uses include pulp and paper, animal feed, composite products such as boards, and chemicals, such as furfural [2].

Impact on soil fertility: Crop residues contribute an interesting array of benefits to the soil from which grain is harvested. These benefits include lowering soil erosion, increasing moisture content, and increasing soil organic matter and total carbon. When removing crop residues from agricultural land, the loss of these benefits must be managed [3].

However, in some situations removal of residues is recommended because they cover too much of the surface and prevent warming of the soil in the spring, delaying seed germination and thus lowering yields (Table 1; [4, 5]). Moreover, too much organic

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Table 1 Potential effects of corn stover harvest [4]

Factor	Benefits of removal	Cost of removal
Economic	Stover sale revenues (\$35/t);	Yield decreases in dry years due to lower soil moisture
	Greater seed germination in colder climates	Yield decreases with increased soil loss; Poorer germination but no yield effect
Fossil fuel use	Increased EtOH production	More field passes required; Fossil fuel needed for conversion to biofuel
Micro-climate	Warmer spring temperatures	Increased evaporation, lower soil moisture
Pests and disease	Increased control for some	Decreased control of others
Carbon and nutrients	Decreased but moderated by tillage and N rate	Nutrient loss predicted greatest in Midwest
Erosion	Moderated by amount of harvest and tillage type	Increased soil loss and water run-off

matter on the surface of the soil also can increase moisture and the threat of increased fungal growth, contributing to diseases. Clearly, the issues vary with location and crop. Each situation will have a unique solution.

The most important practice that will need to be adopted for residues to be sustainably removed from crop land is no-till agriculture. Currently, only 20% of corn acreage and 15% of wheat acreage are cultivated with no-till practices [5]. Tillage increases the rate at which organic matter is decomposed and increases nitrogen losses due to microbial activity. No-till cultivation allows more of the remaining residue to be removed for alternative uses.

Farmer involvement: One of the major concerns with agricultural residues being used for a reliable supply of biomass is compliance of the farmer for collection and delivery of the residues. Because the residues vary by year and region, management of the residues

requires consideration of many factors including maintenance of soil fertility, weather, crop yields, and economics.

The average age of US farmers is 62. This is both an advantage and a disadvantage. The collective experience of farmers is tremendous – management practices are based on their extensive knowledge. In contrast, their retirement is eminent and their replacement uncertain. Their motivation to try new crops is often high though their approach is conservative. Although most farmers may be willing to try new crops, they will approach the change cautiously, planting only a few hectares in the beginning until yield and economics are understood [5]. If the results are economically favorable, in that inputs are lower than harvested material profits, the farmers are often willing to change their practices and participate in the new system. In directed dialogs conducted in 2000–2002, farmers generally agreed that US\$20 ha⁻¹ pre-tax margin would generate their interest in harvesting residues, as long as grain harvesting is not hindered [5]. The value of the residues is not near to the value of the grain, thus logistics and income must make it worth the farmer's time and investment to participate in the residue harvest. The industry estimate for biomass that is delivered to biorefineries is US\$30–\$50 Mg⁻¹ in order to produce commodity ethanol at target prices. However, in order for the farmer to reap a benefit considering the equipment, time, and field issues, the price would have to approach US\$70–\$100 Mg⁻¹. Clearly, policy and logistics research must address this discrepancy.

Logistics and economic issues: Small grains, mostly wheat, produce straw that can be baled and stored. However, the amount available from nonirrigated wheat is minimal after leaving USDA recommended amounts of residue on the ground to improve fertility. If the average dry land wheat straw yield is 2.7 Mg ha⁻¹, and 1.34 Mg ha⁻¹ must be left on the surface to avoid erosion, then less than 2.5 Mg ha⁻¹ of straw would be available for harvest [5]. Because corn stover yields about 11 Mg ha⁻¹, leaving 2.24 Mg ha⁻¹ on the soil surface for organic matter and erosion control, leaves 8.8 Mg ha⁻¹ for harvest. However, in each case if a cover crop is employed, the residues are not required for erosion control and can be harvested in larger amounts.

Because wheat is harvested early in the summer, the straw has low moisture content and can be immediately baled. In contrast, collecting residues as feedstocks from corn fields in particular requires altering harvesting practices. Corn is harvested in the fall and the stover moisture content is usually 30–50%, and must be left in the field to dry, although often fall rains prevent this from happening in a timely manner. In addition, if stover is harvested separately after grain harvest, field machinery must be deployed a second time and this compacts the soil more. The stover that is raked and baled also contains rocks and soil particles which have a negative impact on biorefinery machinery. These issues suggest that one-pass harvesting is an alternative that must be considered.

A detailed description of grain and stover harvesting logistics was recently published [5]. The additional requirements for trucks, combines, and potentially one-pass harvesters, baling equipment, and additional personnel are enormous. The personnel needs are transient in that the harvest window is usually 30–50 days. However, the investment in additional equipment, whether purchased or leased is significant. Harvesting stover while harvesting corn grain requires three times the number of trucks and personnel if using a one-pass harvester. Although this equipment is not yet commercially available, several agricultural machinery manufacturers are designing these harvesters. Because most of the stover currently is either left in the field, tilled under, or used for bedding, or local markets (e.g., corn cobs), baling equipment is not adequate in most farm operations to handle a large increase in biomass harvest. One possible solution could be transporting the field materials to a collection station, possibly associated with a grain elevator operation, and the stover separated from the grain at these off-field locations. The stover then could be stored either as stacked bales or as a wet pile. Bales require protection from the elements, they are dry when baled and must remain dry, at less than 20% moisture, to keep them from deteriorating. In addition, the height of the stacks is limited by the weight and heat that is generated, thus requiring large amounts of field space. However, if the biomass is in compacted, anaerobic, wet piles at greater than 60% moisture, fungal growth is

inhibited and the biomass is very stable [5]. The pile size is only limited by the height of a pump head that continuously recycles the water from a base collection reservoir. This configuration has the added advantage of washing contaminants out of the biomass that were collected from the field. These “haystacks” are large and much higher than bale stacks and thus have far less of a footprint on the ground, minimizing field requirements. Wet storage is a proven industry logistic in that the nonwood fiber pulpers moved to this method of feedstock storage several decades ago.

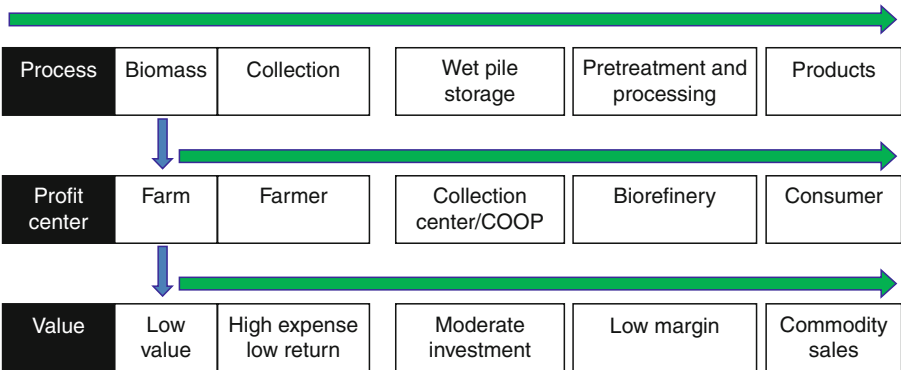
Recommendations: The production of ethanol from corn stover as opposed to grain has significantly more greenhouse gas reduction potential, 79% versus 25%, when burning E85 (85% ethanol with 15% gasoline) on a per km basis [4, 6]. This fact alone motivates development of logistics and infrastructure solutions to develop the industry for all concerned. Nevertheless, county by county plans will be required to sustainably harvest agricultural residues from any crop, based on climate, tillage, and residue type. Farmer networks should be included as part of the value chain to encourage participation (Fig. 1). Small biomass facilities, including portable facilities, could be a positive development for on-farm production of ethanol from excess residues without investment in large biorefinery infrastructure.

Perennial and Annual Herbaceous Biomass Crops

Sugar Crops

Introduction Sugar cane and sweet sorghum which produce sugary syrup in their stems are members of the Panicoid subfamily of the *Poaceae* family [7]. They share the physiologically distinctive and highly productive C4 photosynthetic pathway. The C4 pathway is fundamentally more efficient than the C3 classic Calvin cycle alone and C4 plants are able to convert up to 2% of incident solar energy into biomass [8]. Compared to C3 plants, C4 plants lose less water as they can photosynthesize with stomata nearly closed, thus reducing water loss to the environment and increasing water use efficiency. In addition, plants using the C4 photosynthetic pathway are better equipped to handle high temperatures, drought, and nitrogen limitations than closely related C3 plants [9, 10].

Sugar from sugar-producing plants can be used for direct fermentation into ethanol. Among three major sugar-producing plants, sugar cane and sweet sorghum are adapted to warm temperate to tropical areas, whereas sugar beet is grown only in temperate areas. Sugar cane is the major crop in the Brazilian national ethanol program which produces 15.9 billion liters of ethanol a year [11]. Sweet sorghum is considered to be one of the promising feed stocks for the production of first-generation ethanol. Studies are being conducted to produce ethanol from sweet sorghum sugary syrup



Biomass Crops for Biofuels and Bio-based Products. Figure 1

Agricultural residue value chain. Residue collection and processing must yield value to each link in the chain for the process to be instituted. One solution to this is to have the farmer involved in the collection and storage of the residues to be sold to the biorefinery during the production year

in the USA, India, and China [12–14]. Most ethanol production using sugar beet takes place in Europe; however, using sugar beet to produce ethanol could potentially increase soil erosion and lower net energy balance [15]. All the three sugar-producing plants are a good source for first-generation ethanol production. Compared to sugar beet, both sugar cane and sweet sorghum produce higher biomass and additionally are a good source of lignocellulosic biomass which can also be used for second-generation ethanol production.

Sugar Cane Crystallized sugar from sugar cane was reported in India 5,000 years ago [16]. Sugar cane is a tall perennial grass of the genus *Saccharum*, native to warm temperate to tropical regions of Asia. The plant grows in clumps, and has solid, jointed, fibrous stalks that are rich in sugar. Sword-shaped leaves, similar to those of the corn plant, fold in a sheath around the stem. Mature canes may be 3–6 m tall and

2.5–7.5 cm in diameter (Fig. 2a). All sugar cane species interbreed, and the major commercial cultivars are complex hybrids. Different species likely originated in different locations with *S. barberi* originating in India and *S. edule* and *S. officinarum* coming from New Guinea. Sugar cane is grown in over 110 countries with an estimated total production of 1,627 million Mg in 2009, (FAOSTAT, <http://faostat.fao.org/site/339/default.aspx>) more than six times the output of sugar beet. Brazil is the world's largest producer of sugar cane, producing about one-third of the world's crop, followed by India (FAOSTAT).

Cultivation: Sugar cane cultivation requires a tropical or temperate climate, with a minimum of 60 cm of annual moisture. In prime growing regions of India, Peru, Brazil, Bolivia, Colombia, Australia, Ecuador, Cuba, Philippines, El Salvador, and Hawaii, sugar cane can produce 20 kg m^{-2} biomass exposed to the sun. Although sugar cane species produce seeds, sugar



Biomass Crops for Biofuels and Bio-based Products. Figure 2

(a) Sugar cane. (b) Sweet Sorghum

cane propagation is through stem cuttings of immature canes 8–12 months old, called “setts.” The setts are best if taken from the upper third of the cane because the buds are younger and less likely to dry out. Each sett must contain at least one bud. The setts can be planted at a 45° angle or laid horizontally in a furrow. It takes 12,500–20,000 setts to plant 1 ha. The setts are lightly covered with soil until they sprout (10–14 days) and then the sides of the furrow are turned inward [17, 18]. In the USA and Australia, billet planting is common. Billets harvested from a mechanical harvester are planted by a machine which opens and recloses the ground.

Sugar cane is a perennial crop which usually produces harvests for about 3–6 years before being replanted. The first crop is called the “plant crop” and takes 9–24 months to mature, depending on location [18, 19]. The cane is cut close to the ground because the lower stem has the highest sugar content and low cuts aid in ratooning, the emergence of new crops from the stems and trash (leaves and tops) left behind. Ratoon crops take about 1 year to mature. As many as four or more ratoon crops may be produced before replanting is necessary, mostly due to the slow decline in yields.

The complete sugar cane crop cycle is variable, depending on local climate, varieties, and cultural practices. In Brazil, usually it is a 6-year cycle, in which five cuts, four ratoon cultivation treatments, and one field reforming are performed. Generally, the first harvest is made 12 or 18 months after planting. The following ratoon cane harvests are made once a year, during 4 consecutive years [20].

Sugar cane is harvested by hand and mechanically. Hand harvesting accounts for more than half of the production, and is dominant in the developing world. Mechanical harvesting uses a sugar cane combine, a harvesting machine that can harvest 100 Mg each hour, but machine-harvested cane must rapidly arrive at the processing facility. Once cut, sugar cane begins to lose its sugar content, and damage to the cane during mechanical harvesting accelerates this decline. Some sugar cane varieties are known to be capable of fixing atmospheric nitrogen in association with a bacterium, *Acetobacter diazotrophicus*. Unlike legumes and other nitrogen fixing plants which form root nodules in the soil in association with bacteria, *A. diazotrophicus*

lives within the intercellular spaces of the sugar cane’s stem [21].

Breeding: The goal of cane breeding is to produce an economic yield of sugar that can be sustained over several ratoons. Breeding and selection of cane are not simple processes since viable seeds are seldom produced. Sugar canes are highly polyploid, wind-pollinated outbreeders. They are clonally propagated, highly heterozygous, and intolerant to inbreeding. New varieties are sought from the first-generation progeny of crosses between clones. Five species are of interest to cane breeders. *S. officinarum* ($2n = 80$) has good sugar quality and low fiber, although it is susceptible to most of the main diseases, except gumming disease and smut. *S. spontaneum* ($2n = 40$ –128) is a source of resistance to many diseases, including “Sereh,” mosaic, gumming, red rot, and downy mildew. *S. barberi* ($2n = 82$ –124) are considered the most important breeding canes and are immune to gumming and mosaic and resistant to downy mildew, but susceptible to smut and red rot. *S. sinense* ($2n = 82$ –124) is difficult to breed, but has given rise to some useful breeding lines. *S. robustum* ($2n = 60$ –194) has been used to some extent in breeding lines [22].

Yields: The annual global production of dry cut sugar cane (sugar content: 55% dry basis) is about 328 million Mg. Asia is the primary production region, which produces 44% of the total. South America stands second with a total production of 110 Tg of sugar cane (34%). The annual yield of dry sugar cane ranges from 14 to 22 Mg ha⁻¹ with an average of 17 Mg ha⁻¹. Brazil is the largest single producer of sugar cane with about 27% of global production and a yield of 18 Mg ha⁻¹. The highest yield occurs in Peru, which produces more than 32 Mg ha⁻¹ of dry sugar cane [23].

Diseases and pests: Many diseases and pests affect sugar cane. Bacterial diseases include gumming disease caused by *Xanthomonas vascularum* (Cobb) Dows. Yellowish stripes occur at the leaf tips, leaf blisters occur, and the vascular bundles exude a yellowish gum when cut. *X. albilineans* (Ashby) Dows causes yellow stripes to occur on the leaf blade, many side-shoots are produced, and the vascular bundles of the stalk are red [24]. Fungal diseases such as red rot (*Colletotrichum falcatum* Went), root rot (*Pythium graminicolum* Subr.), pineapple disease (*Thielaviopsis paradoxa* (de Seynes) C. Moreau), downy mildew

(*Sclerospora sacchari* Miy), and smut (*Ustilago scitaminea* Syd.) can also cause damage. Red rot causes the setts to be seriously damaged at low temperatures. Root rot was responsible for the failure of “Otaheite” (a noble cane) in Mauritius in 1846. Downy mildew is currently only found in the western Pacific and was responsible for severe losses in Queensland until rigorous controls were initiated. Smut causes black whiplike organs to emerge from the center of the leaf-roll and affects crops in southeastern Asia and South Africa [18]. Mosaic is a viral disease, whose vectors include *Aphis maidis* Fitch. It was first documented in Java in 1892 and causes severe stunting in some cases. Other viral diseases include ratoon stunting, chlorotic streak, Fiji disease, and Sereh disease. The most destructive insects of sugar cane are stem-borers, the larval stage of several genera of moths. The larvae burrow into the stem and on emergence cause weakened stems and loss of sucrose. Biological control and use of transgenic *Bt* sugarcane are the most efficient control for these insects [18].

Commercial and industrial use: Sugar cane has many industrial uses and is one of the most widely used and cheapest sources of domestic products, including table sugar, molasses, and ethanol. Cane juice contains 10–20% sucrose and about 1 Mg ha⁻¹ of raw sugar can be extracted from 8 to 9 Mg ha⁻¹ of cane. Molasses is a by-product of the manufacturing of cane sugar. It is residual syrup from which no more crystalline sucrose can be obtained by simple techniques. Approximately 2.7% of cane can be extracted as molasses, which can be used as an animal feed as it has high carbohydrate

contents. Molasses along with cane juice and other by-products can be fermented to produce an alcoholic distillate, rum, or similar liquors. Ethanol is also produced from molasses, which can be used in vinegar, cosmetics and pharmaceuticals, cleaning preparations and solvents, and coatings [16]. One of the important uses of ethanol is as a transportation fuel (see below). Still other products from molasses are butanol (a solvent), lactic acid (a solvent), citric acid (mostly for foods and beverages), glycerol, and yeast media [25].

Sugarcane as a bioenergy crop: Sugar cane being a C4 plant is one of the most efficient photosynthesizers in the plant kingdom [26]. Sugar cane’s high concentration of sugar, which is readily available to microorganisms, makes it uniquely suitable for ethanol production. As a producer of sugar for fermentation bio-products, sugar cane is found to have advantages in relation to fossil-energy input, emissions of greenhouse gases, and possibly acidification, when compared with corn and sugar beet [15]. Another useful by-product of sugar production is bagasse, the fibrous residue left after the juices are extracted from the cane. It is the main source of fuel in sugar factories. It can also be used in paper, cardboard, fiber board, and wall board [27]. It is quite possible that further uses of sugar cane will be developed in the future, but even now it can be seen that sugar cane is a very important and useful plant crop worldwide. Uses of sugar cane in different parts of the world are shown in Table 2. The resulting energy and greenhouse gas benefits of sugar-cane-derived products have been shown previously [28]. For sugar cane, the main co-product is surplus energy

Biomass Crops for Biofuels and Bio-based Products. Table 2 Uses of sugar cane [23]

	Feed (%)	Seed (%)	Waste (%)	Food manufacture (%)	Food (%)	Other uses (%)
Africa	0.14	2.02	2.12	89.43	4.44	1.85
Asia	3.14	4.68	1.13	86.19	4.57	0.30
Europe	0.18	0.00	0.00	87.90	0.00	11.92
North America	0.00	5.37	0.00	94.62	0.00	0.00
Central America	1.80	0.25	1.06	95.40	0.05	1.45
Oceania	0.00	0.00	0.00	99.99	0.01	0.00
South America	0.98	0.00	0.68	97.83	0.27	0.24
World	1.91	2.35	0.97	91.88	2.40	0.48

from bagasse. The most successful story of using sugar cane as a bioenergy feed stock is in Brazil. Brazil is considered to have the world's first sustainable biofuels economy and is the biofuels industry leader. Its sugar cane ethanol program is considered a model for other countries and is the most successful alternative fuel program to date. Brazil's 40-year-old ethanol fuel program is based on the most efficient agricultural technology for sugar cane cultivation in the world. It uses modern equipment and cheap sugar cane as feedstock. The residual cane-waste (bagasse) is used to produce heat and power, which results in a very competitive price and a high-energy balance (output energy/input energy). This energy balance varies from 8.3 for average conditions to 10.2 for best practice production. Brazil is recognized as the world's second-largest producer of ethanol (DOE-EIA, 2007, <http://www.eia.doe.gov/emeu/cabs/Brazil/full.html>). Brazil and the USA lead the world in global ethanol production, accounting for nearly 70% of the world's production. Brazil produces approximately 37% of the world's total ethanol and 48% of the world's ethanol uses as fuel. They began promoting the production of crops for ethanol in the mid-1970s after the first global energy crisis. In 2008, 454,000 barrels per day (bbl/day) of ethanol were produced, up from 365,000 in 2007. Because ethanol production continues to grow faster than domestic demand, Brazil has sought to increase ethanol exports, becoming the largest ethanol exporter in the world, holding over 90% of the global export market. According to industry sources, Brazil's ethanol exports reached 86,000 bbl/day in 2008, with 13,000 bbl/day going to the USA (DOE-EIA, 2007).

Sugar cane bagasse is the residue obtained after crushing of sugar cane during sugar production and consists of cellulose 43.6%, hemicellulose 33.8%, lignin 18.1%, ash 2.3%, and wax 0.8% on a dry weight basis [29]. About 180–280 kg ha⁻¹ of sugar cane bagasse could be produced after squeezing [30]. The second-generation process revolves around accessing the large amounts of cellulosic material blocked within the lignin-based shell and creating ethanol from it [31]. Currently the leftover bagasse is burned to co-generate power. In the future, the process should be similar, but instead of burning all of the bagasse, the material will be sorted so that the cellulose and hemicellulose are processed further into cellulosic ethanol with only the

remaining high-lignin content materials being used as an alternative energy source. The move toward utilizing sugar cane bagasse for the production of ethanol instead of power generation is a question of economics. The current process of burning the bagasse for energy is not as energy efficient as using it to produce ethanol. Theoretically, 1 Mg of sugar cane bagasse can produce up to 300 L of ethanol. In reality the yield depends on a number of parameters including efficiency of the process. Currently, 6,000–7,000 L of ethanol is produced from 1 ha of sugar cane-not including the bagasse. When bagasse can be utilized for ethanol production, the output could double to 12,000–15,000 L ha⁻¹ [31].

Sweet Sorghum Sweet sorghum is a C4 crop in the grass family belonging to the genus *Sorghum*, which also includes grain and fiber sorghum and is characterized by high photosynthetic efficiency. Sweet sorghum is of interest as a dedicated agricultural energy crop because of its drought tolerance, relatively low input requirements and ability to produce high yields under a wide range of environmental conditions [12, 32]. These traits make sweet sorghum a potentially important feedstock for bioenergy production, mainly in regions where conditions are not favorable for growing starch-rich crops such as maize. The great advantage of sweet sorghum is that it can become dormant under adverse conditions and can resume growth after relatively severe drought which has implications for crop management. Sweet sorghum is typically an annual, but some cultivars are perennial. Like other sorghum types, sweet sorghum probably originated from East Africa and spread to other African regions, Southern Asia, Europe, Australia, and the USA. Plants grow in clumps and height of stalks ranges from 0.8 to 4 m (Fig. 2b). The thickness of stalks also varies, ranging between 1.25 cm and 3.75 cm. Prop roots regularly grow from the lower nodes. Seeds are produced by self-pollination from a panicle that emerges at the top of the plant and contains both the male and female inflorescences. Seeds are small, round, and may be white, yellow, brown, or red in color. Each panicle can produce up to 4,000 starch-containing grains. Although native to the tropics, sweet sorghum is well adapted to temperate climates. Like its close relative sugar cane (*Saccharum* spp.), sweet sorghum has been selected to accumulate high levels of edible sugars in

the stem. Sweet sorghums are tall and produce high biomass in addition to sugar. In all varieties, the primary carbohydrate is sucrose, with variable amounts of reducing sugars and starch [33].

Cultivation: Sweet sorghum is very drought resistant and shows good adaptability to poor soil types including saline soils. It has a very short vegetation period and thus is ideal for double cropping, either three crops of sweet sorghum or with an alternative crop [13]. Propagation is accomplished through seeds. It is easily grown in areas that are too dry for maize. Seeds are typically sown in widely spaced rows (75–100 cm) manually or using a corn planter in spring after the rainy season and as soon as the soil temperature remains above 15–18°C. The ideal seeding rate for most sweet sorghum varieties is 3–4 seeds per foot of row with a final stand of 2–3 plants per foot of row. If plant populations are too high, the canes will be spindly and contain less juice than an equal tonnage of larger diameter canes. Seed germination takes place within 24 h in warm and moist soils, and the time to maturity lies between 90 and 120 days. The plant grows to a height of from about 1.2 to above 4 m, depending on the varieties and growing conditions. Even though sweet sorghum is predominately self-pollinating, hybrids and crosses can be produced using male-sterile maternal parents. Sugar content in the juice increases with maturity, and is low prior to seed development. Controlling nitrogen fertilizer and its application time promotes sucrose content and growth rate in sweet sorghum. Application of adequate amounts of K fertilizer increases yield responses more than high levels of nitrogen fertilizer alone [34]. Currently, the only commercially viable harvest method for sweet sorghum is removing the entire crop with a forage harvester and transporting it to a mill/pretreatment/ethanol facility. Bennett and Anex [12] indicate that fermentable carbohydrates can be produced at less expense from sweet sorghum than from corn grain. Further results on costs associated with off-farm transportation, storage, or capital costs associated with milling and energy recovery equipment reevaluates sweet sorghum as a biocommodity feedstock [12].

Breeding: Roughly 4,000 cultivars of sweet sorghum are distributed throughout the world [35] providing a diverse genetic base from which to develop regionally specific, highly productive cultivars. In addition to

producing large amounts of sugar-rich biomass, hybrids can be developed from crosses between grain-type seed parents and sweet-type pollen parents [36]. The product of these crosses typically increases biomass yields and sugar content when compared to the original grain-type seed parents. Such hybrids can co-produce grain at levels approaching the yields of the grain-type seed parent [37]. The co-produced, protein-rich grain can be consumed as food, animal feed, or converted to bioproducts like ethanol [13, 36]. Proper variety selection will play a large role in the success of sweet sorghum production for ethanol. The ideal variety for a particular location should produce high yields with minimal inputs, have a high percentage of high quality and easily extractable juice, be disease and insect tolerant, and tolerate both drought and wet conditions.

Yields: Sweet sorghum yields vary considerably depending on the varieties/hybrids that are used, the location (soil, water, climate, pests and diseases), inputs, and production practices. The annual global production of dry sorghum is about 53 Tg with the an average yield of 1.2 Mg ha⁻¹. The USA is the largest producer of sweet sorghum (23%) at a yield of 3.7 Mg ha⁻¹. The highest yield occurs in Israel and Jordan, which produce more than 10 Mg of dry sorghum per hectare [23]. When considering sweet sorghum for ethanol production, the most important yield components are biomass yield, juice yield, and sugar production per hectare. The concentration of soluble sugars in sorghum ranges widely depending upon variety. Biomass yields of sweet sorghums are also variable ranging from 20 to 120 Mg ha⁻¹ and juice content from 65% to 80% of biomass. The combined sugar content of the juice varies between 9% and 15%. Sugar yields vary from 4 to 17 Mg ha⁻¹. The bagasse (crushed stalks) and leaves make up the remainder of the wet biomass. The bagasse represents approximately two-thirds of the dry matter and leaves represent the remaining portion. Fermentation of the sugar in the juice yields 600–900 L ha⁻¹ of ethanol [38].

Diseases and pests: Disease and insect problems may also limit yield potential, suggesting that further research in this area is essential. Leaf diseases are the most troublesome for forage producers. These are anthracnose caused by *Colletotrichum graminicola* (which can be overcome by using resistant varieties) and leaf blight caused by *Helminthosporium turcicum*.

Charcoal rot (*Macrophomina phaseoli*) causes plants to lodge badly. Grain may be affected by covered smut (*Sphacelotheca sorghi*) in which the seed is replaced by a sac of spores; fungicidal seed treatment before planting prevents this latter malady (FAO, 2009, <http://www.fao.org/ag/agp/agpc/doc/gbase/data/pf000319.htm>). From a forage point of view, grasshoppers appear to be the worst pest, and feral pigs can damage the crop in some locations. Grain pests include the sorghum midge, *Contarinia sorghicola*, whose larvae feed on the developing seeds. Bird damage is also important with the weaver bird, *Quelea quelea*, causing major losses in Africa. Damage can be prevented by using awned varieties of sorghum, giving some hope of reducing losses. The high tannin content of sweet sorghum seed is another deterrent, and early harvesting for silage avoids the major problems.

Commercial and industrial use: Worldwide, the major uses of sweet sorghum are animal feed (49%) and human food (40%; Table 3). In Africa and Asia, over 60% of sweet sorghum is used for human food. In the other regions, most sorghum is used for animal feed. There is no use of sorghum for human food in Europe and South America. Although the juice, grain, and bagasse from sorghum provide many opportunities, most applications around the world are for syrup and forage. An average yield of 1,900 L ha⁻¹ of syrup can be achieved, although yields of 800–1,200 L ha⁻¹ can result if weather conditions are poor. In forage applications, chickens can be fed with seed heads and ruminant livestock can use the grains, leaves, and stalks. The organic by-product from sweet sorghum

syrup processing is often fed to livestock, left on the field, or composted. Sweet sorghum bagasse is used currently to manufacture chemical pulp. The quality of the pulp obtained is excellent for the paper industry. Sweet sorghum can be considered as a major raw material for the paper industry [39].

Sweet sorghum as a bioenergy crop: Sweet sorghum is attractive for bioethanol production because of its high fermentable sugar content and very high yield of green biomass (20–30 dry Mg ha⁻¹), its low requirement for fertilizer, high water use efficiency, and short growth period; and, it is well adapted to varied climate and soil conditions. These advantageous agricultural characteristics make sweet sorghum a promising substitute feedstock for fuel ethanol production in the southern USA [32]. Based on a recent economic analysis, sweet sorghum is considered to be one of the most drought-resistant crops and has higher biomass yield and lower production costs than many other plants [40]. Sweet sorghum can produce fermentable sugars (sucrose, glucose, and fructose) in its juice, starch in its grain, and lignocellulose, which can be used in both current starch-based ethanol plants and future cellulosic ethanol plants. Of the 20–30 dry Mg ha⁻¹ of biomass, approximately 40–45% is fermentable sugars and starch, equivalent to more than 500 bushels ha⁻¹ of corn yield. If all fermentable sugars in sweet sorghum are converted to ethanol, potential ethanol yield could be 5,500–6,100 L ha⁻¹. However, normal pressing can recover only ≈50% of the total sugars in the sorghum stalk [41]. Increasing the juice yield or making proper use of remaining sugars in the bagasse is crucial for

Biomass Crops for Biofuels and Bio-based Products. Table 3 Uses of sweet sorghum [23]

	Feed (%)	Seed (%)	Waste (%)	Food manufacture (%)	Food (%)	Other uses (%)
Africa	6.90	2.01	13.02	5.21	72.76	0.11
Asia	32.29	2.21	4.94	0.00	60.52	0.04
Europe	98.76	0.53	0.71	0.00	0.00	0.00
North America	86.80	0.30	0.00	0.00	3.03	0.00
Central America	94.85	0.38	2.19	0.00	2.58	0.00
Oceania	97.71	0.39	0.04	0.11	1.75	0.00
South America	95.09	0.69	4.21	0.00	0.00	0.00
World	49.10	1.39	6.11	3.20	40.15	0.05

realizing the high ethanol yield of sweet sorghum and is of important economical value.

Similar to sugar cane bagasse, sweet sorghum bagasse is the residue obtained after crushing of sweet sorghum cane for sugar production and consists on average of cellulose 34%, hemicelluloses 25%, lignin 18%, and ash 4% on a dry weight basis [42]. Sweet sorghum bagasse was found to be a remarkable raw material for the paper industry, yielding high-quality pulp [39]. The most promising future utilization of bagasse is cellulose-based ethanol production, while the residual solids (mainly lignin) can be burned to provide heat and power. Hydrolysis of the cellulose and hemicellulose fractions can be catalyzed by acids or cellulolytic enzymes. Enzymatic processing needs a pretreatment step to increase the susceptibility of the cellulose, which can be degraded by cellulolytic enzymes to glucose.

***Miscanthus* and Switchgrass – Dedicated Perennial Energy Crops**

Introduction *Miscanthus* and switchgrass are two perennial herbaceous crops with attributes generally considered as ideal for biomass crops, making them well suited as dedicated energy crops for biofuel production (Table 4). They are members of the grass family, *Graminae* (*Poaceae*). The perennial herbaceous crops have long-lived roots that may establish beneficial interactions with root symbionts, facilitating acquisition of mineral nutrients from the soil which may result in lesser amounts of fertilizer needed [44]. This can translate into cost saving on fertilizer and minimizing water pollution from leachates and runoff. A very important physiological characteristic of the perennial herbaceous crops is the recycling of nutrients within the plants. Nutrients are moved from roots to growing shoots at the beginning of each growing season and from the senescing shoots to the roots at the end of the growing season [45]. This recycling characteristic gives the perennial herbaceous crops many advantages over other plants and at the same time reduces the amount of fertilizer needed. In spring, when mineral nutrients are translocated from the roots to the shoots, the perennial grasses get a rapid start in forming a photosynthetically active canopy leading to biomass accumulation when many annuals are still seedlings.

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Table 4 Attributes of an “ideal” biomass crop [43]

The “ideal” biomass crop?	Corn	Short-rotation coppice ^a	Perennial grass
C4 photosynthesis	★		★
Long canopy duration		★	★
Recycles nutrients to roots			★
Clean burning			★
Low input		★	★
Sterile (noninvasive)	N/A	★	<i>M. giganteus</i>
Winter standing		★	★
Easily removed	★		★
High water use efficiency			★
No known pests or disease			<i>M. giganteus</i>
Uses existing farm equipment	★		★

^aCoppice is a grove of densely growing small trees pruned to encourage growth

Conversely, in fall, mineral nutrients from the senescing shoots are transferred to the roots where they are stored over the winter. This has the positive effect of lowering the ash content of the shoots, improving their overall energy content and quality for biofuel production and at the same time improving the viability of the roots during the cold winter. Another advantage of the perennial grasses is the low input cost in establishing the crops. Once the perennial grasses are established, they can be harvested annually without replanting and no tillage is needed for the next 15–20 years. This leads to a substantial saving in labor cost and at the same time reduces soil erosion and nutrient loss. *Miscanthus* and switchgrass are C4 plants [46]. A higher solar energy conversion rate should lead to a higher total biomass yield per unit of land area. Perennial grasses are also known to exhibit increased soil-carbon levels by sequestering portions of atmospheric carbon in the soil in root biomass and in root

turnover creating soil organic matter. The perennial herbaceous crops therefore, represent significant soil carbon sinks [47]. The perennial grasses are also known to be better adapted than conventional crops to different types of soils which means they can also be grown on marginal land not used for food crops.

***Miscanthus* Origin and distribution:** *Miscanthus* is native in many parts of Asia such as China, Japan, and the Pacific Islands, and can grow up to 4 m tall. *Miscanthus* was first introduced into Denmark from Japan in 1935 as an ornamental plant and is now cultivated throughout Europe and North America primarily for energy production with other end uses being explored. It is estimated that there are about 14 species of *Miscanthus* [48] and the most common species investigated as a biofuel in Europe and North America is *Miscanthus* \times *giganteus*, a naturally occurring sterile triploid hybrid that has its origin in Japan [49]. The genetic origin of *M. \times giganteus* is uncertain but some evidence suggests that this hybrid is a result of a cross between *M. sinensis* (diploid) and *M. sacchariflorus* (tetraploid) [50]. In general, *M. sinensis* types are well adapted for cooler climates, whereas *M. sacchariflorus* can provide genetic resources for warmer regions [51].

Growing conditions: Extensive studies and evaluation of *Miscanthus* as a biomass resource for biofuel and bio-based products have been going on in Europe for the last 2 decades under the umbrella of the *Miscanthus* Productivity Network [52]. These studies have provided much of the currently available information on *Miscanthus* as a renewable feedstock for bioenergy. In recent years, similar studies have also been conducted in the Midwest of North America but on a smaller scale. The studies in Europe were conducted in 15 cities from southern Italy (37° N latitude) to Denmark (56° N latitude) [53]. Although *Miscanthus* prefers the mild temperatures and high water availability of its natural habitats in the tropics and subtropics, the successful establishment of *M. \times giganteus* in Europe and North America suggests that it is relatively tolerant of temperate temperatures and low water availability. In North America, *M. \times giganteus* has been established successfully in the Midwest from latitude 38° N to 48° N covering Ohio, Michigan, Indiana, and Illinois, and expanding into other areas in the south like Georgia and Florida and

as far north as Quebec, Canada. *M. \times giganteus* has been demonstrated to be more tolerant of low temperatures than most C4 perennials [54, 55]. Nevertheless, low temperature still limits the growth of *Miscanthus*. It is estimated that *Miscanthus* requires a minimum of 500 mm of annual rainfall and where the annual rainfall is typically below that amount, irrigation is necessary for substantial growth and biomass yields [53]. *M. \times giganteus* can adapt to a wide range of soil, from sands to high organic matter soils. It is also tolerant to a wide range of pH, the optimum being between pH 5.5 and 7.5 [56]. Generally, areas with higher rainfall and soils with high water-holding capacity will favor production of *Miscanthus*. Limited soil water availability during the growing season will decrease production.

M. \times giganteus being a sterile hybrid is established from rhizomes. The rhizome pieces, approximately 200 mm in length, are planted directly into the soil at a depth of 200 mm [56]. Fresh rhizomes are generally used because rhizomes stored for a period of time are likely to dry out and exhibit less vigor. Planting takes place after the risk of the latest spring frost is over, typically between March and May. The annual fertilizer requirement is very low. Results from field trials in Europe and from reviews of literature showed that nitrogen has only a modest influence on the yields of *M. \times giganteus* [43]. It is estimated that the annual requirement of nitrogen is 50–70 kg ha⁻¹, phosphorus is 5–10 kg ha⁻¹ and potassium is 70–100 kg ha⁻¹ [56, 57].

Harvesting is carried out after the crop has senesced with moisture content preferably at its lowest and with nutrients translocated into the rhizomes. Harvesting is timed to achieve a balance between attaining lowest moisture content and minimizing biomass losses caused by adverse winter conditions. Crops grown in cooler climates are typically harvested in early spring when moisture content is lowest. Crops grown in warmer climates reach their maturity earlier and can be harvested in late autumn or delayed until early spring. However, delaying harvest until early spring will result in yield reduction by as much as 30–50% due to winter losses of dead and decaying leaves and upper stem parts. But such losses are tolerated because the lower moisture content (20%) improves the fuel quality, permits ease of handling, and requires little drying.

Yield: *Miscanthus* takes about 2–3 years to establish and so the first-year crop does not yield sufficient biomass to merit harvesting. The crop is normally harvested from the second year onwards but yields will continue to improve after year two until they level off. Ceiling yields can be reached in 2 years under good growing conditions but may take up to 5 years at some locations. The ceiling yields are attained more quickly in warmer climates and those total yields are higher than in cooler climates. The winter yields reported for Europe following the third growing season varied with location and ranged between 6.4 and 23.6 Mg ha⁻¹ from northern to southern Europe [53]. Data on *Miscanthus* productivity in North America are still lacking but mathematical productivity modeling [58] based on the European studies projected yields of *Miscanthus* in the Midwest to far exceed those of switchgrass [43]. A recent report comparing productivity of *Miscanthus* and a locally adapted switchgrass cultivar (Cave-in-Rock) grown side by side in field trials in Illinois seems to support the projection [59]. The reported average winter yields of dry matter for the 3 years following the third growing season were 19, 30.3, and 31.4 Mg ha⁻¹ in the northern, central, and southern plains, respectively [59]. The average yield per year across the three sites is approximately 27.2 Mg ha⁻¹. This yield is significantly higher than the yields reported in Europe and almost three times

higher than for switchgrass cv. Cave-in-Rock, grown side-by-side with *Miscanthus* in the same field trials (Table 5). A yield of 27.2 Mg ha⁻¹ would achieve the projected target of 342 million Mg on 12.6 million hectares, half the area estimated in the billion-ton-study projections [1]. No disease has been reported to date for *Miscanthus* but the crop has been known to be susceptible to *Fusarium* blight and Barley Yellow Dwarf Luteovirus [52]. Weed control is essential during the long establishment phase. Fields are typically sprayed with herbicide before planting followed by at least two sprayings a year for the first 2–3 years.

Uses: *Miscanthus* is grown primarily to be used in the bioenergy industry. It is being tested in Europe as solid fuel for combustion in farm-heating plants as well as for co-combustion with coal, straw, and wood to generate power [53]. Its potential lies in the abundance of raw cellulose biomass that can be converted to cellulosic ethanol. Nonenergy applications for *Miscanthus* include material for thatching [60], paper pulp production [61], and as a bio-composite in construction/building materials such as panel board and building block [62] and as a substitute for the plastics or light metals in the core of light natural sandwich material (LNS). LNS materials are light building materials used for plane and molded structural parts with high form stability at low weight, used for a broad range of applications. Such substitutions are used in carrying cases for

Biomass Crops for Biofuels and Bio-based Products. Table 5 Comparison of mean harvestable dry matter, Mg ha⁻¹ (± 1 SE), at the time of peak biomass production (Hmax), and after complete plant senescence (H1) from *Miscanthus* (M) and switchgrass (S) grown at three locations in the Midwest USA during 2004–2006 ($n = 4$) [59]

Year	Harvest time	North		Central		South		State average	
		M	S	M	S	M	S	M	S
2004	Hmax	38.1 (5.7)	*	60.8 (3.9)	26.0 (3.1)	48.5 (1.8)	*	48.3 (3.5)	26.0 (3.1)
	H1	13.7 (1.6)	*	25.1 (2.5)	12.8 (1.2)	37.3 (3.0)	*	25.4 (3.2)	12.8 (1.2)
2005	Hmax	25.6 (1.1)	7.8 (0.6)	40.7 (2.3)	11.5 (1.8)	40.4 (4.1)	7.8 (0.6)	33.3 (2.6)	7.9 (0.8)
	H1	13.7 (1.6)	7.8 (0.6)	31.1 (3.2)	10.6 (1.3)	27.3 (5.7)	7.8 (0.6)	25.8 (3.8)	7.9 (0.8)
2006	Hmax	29.9 (3.3)	8.4 (0.9)	44.1 (2.6)	22.0 (5.2)	51.3 (2.6)	9.6 (2.9)	39.0 (4.6)	15.6 (2.6)
	H1	29.9 (3.3)	7.7 (1.0)	44.1 (2.6)	15.6 (2.6)	39.2 (2.9)	9.1 (2.6)	37.7 (2.4)	15.6 (2.6)
3-year	Hmax	31.2 (3.7)	8.1 (0.5)	45.5 (3.9)	19.8 (2.6)	42.3 (3.6)	8.7 (1.8)	38.2 (2.3)	12.5 (1.8)
average	H1	20.9 (2.4)	7.8 (0.6)	33.4 (2.8)	13.0 (1.1)	34.6 (2.6)	6.7 (1.1)	29.6 (1.8)	29.6 (1.8)

*Data is not available for these points. Bold values highlight geographic and temporal averages of both parameters in both species

musical instruments and lab tops, rotor blades of wind power stations, small boats, and parts of yachts [63].

Future directions: One of the drawbacks of using *Miscanthus* as a biomass crop is its narrow genetic base. However, efforts have been undertaken to broaden the genetic base of *Miscanthus* and maximize the productivity and adaptive range of the crop through traditional breeding as well as modern genetic engineering by the European *Miscanthus* Improvement (EMI) project (www.biomatnet.org/secure/Fair/F659.htm) and research institutes across North America. Even with an unimproved *Miscanthus* crop, the yields achieved so far look very promising. Therefore, yield would be expected to increase dramatically and the cost of production to fall with breeding improvement efforts. A potential hybrid of *M. sinensis* that combines winter hardiness with high biomass potential has been identified through the effort of the EMI project. This hybrid will result in improved crop quality through delayed harvest without significant loss in yield [53]. The high cost of establishment is another major concern associated with cultivating *Miscanthus* as a biomass crop. This concern can be addressed with improvement in farming equipment and farming practices that will help to reduce loss of harvested material, time, and labor cost. The development of new machinery to process rhizomes (that includes lifting, cleaning, splitting, sorting and boxing) and carry out precision rhizome planting has made commercial rhizome multiplication farming and commercial production of *Miscanthus* feasible. Improvement in the crop together with improvement in farming technology and processing of this biomass crop into fuel will undoubtedly make *Miscanthus* a very attractive crop to the biofuel industries.

Switchgrass Origin and distribution: Switchgrass (*Panicum virgatum*) is a warm-season grass indigenous to the Central and North American prairie with its northern limit of adaptation at about 51° N [64]. In the USA its adaptive range stretches from the eastern seaboard to as far west as the east side of the Rocky Mountains and from the Texas Coastal Plain to as far north as Hudson Bay [65]. This wide geographic distribution can be seen as the manifestation of the great genotypic and consequently phenotypic variation seen within the species.

In addition to its broad adaptation, switchgrass exhibits great adaptability to diverse edaphic conditions. Switchgrass can reach the height of 0.5–3 m or more in wetter areas of the country. Switchgrass has been extensively studied and planted in North America. Historically, switchgrass grown in the USA has been used as forage but over the last 2 decades it has been investigated intensively for its potential as an energy crop. In 1991 switchgrass was identified by the US Department of Energy for development as a model herbaceous energy crop because of its ability to tolerate a wide range of environmental conditions and at the same time offer high biomass yield [66].

Ecotypes: A fair amount of genetic variability exists in the switchgrass populations found across North America. The environment exerts a selective pressure on the population's diverse genotypes. The interaction between environment and genotype has over time created different ecotypes as well as variations within an ecotype (reproductive phenology, cold, heat, and drought tolerance) resulting in varieties with specific genetic and morphological characteristics that provide a good "fit" to a particular region. Through natural selection, two genetically and phenotypically distinct types of switchgrass have emerged, the lowland and the upland varieties (Table 6) [68]. The lowland varieties are vigorous, tall, thick-stemmed and generally found in wetter and more southern habitats. The upland forms are typically shorter and fine-stemmed and mainly found in drier mid- and northern latitudes. The ecotypical differences are generally related to local soil and climatic characteristics, with eastern and southern varieties adapted to higher moisture conditions, and western and northern varieties adapted to drier conditions. The phenotypic and ecotypic variation between the lowland and the upland ecotypes can be explained by their cytotypic diversity. Lowland switchgrass ecotypes are tetraploid, with a base chromosome number of 9 (diploid number 18), leading to 36 chromosomes ($2n = 4x = 36$). Upland ecotypes with the exception of the cultivar Summer, which is tetraploid, are octoploid ($2n = 8x = 72$) and less frequently, hexaploid ($2n = 6x = 54$) [69]. Breeding programs aimed at improving the forage yield have developed cultivars that adapt to specific locales ensuring the success of switchgrass in a large variety of conditions,

Biomass Crops for Biofuels and Bio-based Products.**Table 6** Characteristics of Upland and Lowland switchgrass ecotypes [67]

Upland ecotypes	Lowland ecotypes
Developed on higher “mesic” (moderately moist) sites	Developed in lower lying, “hydric” (considerably moist) sites, more sensitive to moisture stress
Adapted to mid- to northern latitudes	Adapted to lower latitudes
Predominantly octaploid ($2n = 7x = 72$)	Tetraploid ($2n = 4x = 36$)
Longer root length and internodes	Bunch form, larger root diameter
Shoots: originate from more active rhizomes and basal nodes of previous year culms	Shoots: originate from buds on rhizomes
Shorter and fine stems	Taller, coarser, thick stems, long, wide bluish-green leaves with long ligules, large panicles

from arid sites in the shortgrass prairie to brackish marshes and open woods [70].

Growing conditions: Switchgrass will grow in a wide range of soil types from fine to coarse textured soils but prefers soils of finer texture. Loamy and sandy soils will allow the roots and crown to spread more easily than do denser clay soils. Sandy soils dry out quickly potentially limiting the establishment success and biomass yield. Switchgrass can grow in acidic soil with pH as low as 4.3 [71] but optimum growth occurs at a pH between 5.0 and 8.0 [72]. Lowland switchgrass fares better in heavier and wetter soils while the upland types favor drier soils. Within the species, upland types are generally considered more drought tolerant [73]. Switchgrass grows best in association with site-adapted mycorrhizal fungi. The presence of mycorrhizae is thought to enhance phosphorus uptake by the plants [74, 75]. Therefore, mycorrhizae play a key role in moderating switchgrass growth in phosphorus-limited environments as well as reducing fertilizer inputs for biofuels production. Warm soil temperature and

moisture are important in the successful establishment of switchgrass. Once established, switchgrass can survive extreme periods of drought. Under nonirrigation conditions switchgrass grows best in areas with greater than 500 mm of average annual rainfall.

Switchgrass seed germination is temperature and pH sensitive [72]. The optimum temperature for germination and growth are cultivar-dependent. Some cultivars such as the southern uplands germinate at about 11°C [76] while other cultivars may require as high as 35°C to germinate [77]. Planting is typically done in spring from mid-March to late May. Dormant seeds require a breaking step for them to germinate. Dormancy-breaking can be achieved by stratification. Planting dormant seeds into a cool soil (10–20°C) and allowing them to stratify in situ has been shown to increase germination [77] but this may lead to weed control problems. The cool season weeds can germinate first and choke out the switchgrass seedlings when the soil warms [78]. Weed control is very important in the early stages of establishment. Unfortunately, there are very few herbicide options available to control the weeds after switchgrass emergence. The herbicides almost universally used for some time as pre- or post-emergent herbicides for switchgrass and other warm-season grasses are triazines [79–82]. However, the types of herbicides and the rates used will best be determined by considering the weed species to be controlled and switchgrass’ tolerance to the chemical.

Most research on switchgrass fertility has focused on its use as forage and higher nitrogen applications can ensure high yields and better quality feed. Nonetheless, some researchers have considered nitrogen fertilizer recommendations for switchgrass to be higher than necessary for biomass production. Switchgrass has a remarkable ability to extract nitrogen from unfertilized soils and is inherently thrifty in its use of phosphorus and potassium and often shows little or no response to additions [83, 84]. Mineral cycling within the plant and the presence of mycorrhizae in the soil play an important role in nitrogen and phosphorus nutrition of switchgrass. Switchgrass as a biomass crop in general can be grown without fertilizer or limited addition of fertilizer and still maintain productivity [67]. The nitrogen, phosphorus, and potassium recommendations should ideally be specific to a site or soil.

Harvesting switchgrass for biomass as opposed to forage should preferably be delayed until shoots have essentially all senesced and died which may not be until November or December. This will allow nutrients to be recycled from shoots to below-ground parts at the end of the growing season [85]. Harvesting once per year in late fall or early winter is recommended to maintain the highest sustainable biomass yields in the long term [67]. Harvesting late in the fall or early winter allows moisture content of the crops to drop to 15% or less which will facilitate quick baling and ease of transport as well as improving the quality of the biomass feedstock. For co-firing in coal plants the moisture content should preferably be around 12% to 13% [86]. Harvesting can be carried out with conventional haying equipment.

Yield: Switchgrass becomes fully productive only upon the third year after planting. Unlike other crops where yield data have been available for many years, data for switchgrass as a biomass crop are rather limited and are based mainly on small-plot research. A search across the literature provides switchgrass yield estimates that vary considerably, from less than 0.9 Mg ha⁻¹ to almost 36.3 Mg ha⁻¹. Nonetheless, the most frequently observed yield class across all ecotypes, cultivars, soils, and management practices is between 9 and 10.9 Mg ha⁻¹. This great variability in yields is explained by the wide range of ecotypes as well as the strong interactions between genotypes and the environment. Gunderson et al. [70] observed higher yields on average within the lowland cultivars, 11.9 Mg ha⁻¹ versus 8.4 Mg ha⁻¹ in upland cultivars. Among the lowland varieties Alamo and Kanlow give the highest yield while Cave-in-Rock gives the highest yield for the upland varieties [87].

With newer varieties of switchgrass, yields in excess of 18.2 Mg ha⁻¹ have been reported for test plots. Sanderson et al. [88] have reported yields of 13.6–18.2 Mg ha⁻¹ in field trials in Texas and Thomason et al. [89] have reported yields in excess of 27.2 Mg ha⁻¹ from field work in central Oklahoma. These yields are relatively high and site-specific. In a larger scale study, Parrish and Fike [67] reported average biomass yield in a 10-year study of 12.9 Mg ha⁻¹. Schmer et al. [90] reported on-farm yields ranging from 4.7 to 10.1 Mg ha⁻¹ for field trials in the USA. According to the US Agricultural Research Service,

growers can expect yields from 15.4 to 36.2 Mg ha⁻¹ in the southeast, 10.9–13.6 Mg ha⁻¹ in the western Corn Belt, and 2.3–9.1 Mg ha⁻¹ in the northern plains [91].

Uses: Switchgrass was originally used as forage, either grazed [92, 93] or for making hay [94, 95]. The use of switchgrass has since been expanded to include nonforage purposes such as for bioenergy, soil stabilization and erosion control in critical areas like strip-mine soils, sand dunes, and dike, and soil improvement in areas degraded by overcropping. “Alamo” switchgrass has also been tested for its ability to remediate soils contaminated with cesium-137 and strontium-90, two radionuclides released during nuclear testing, nuclear reactor accidents, and weapons production. The level of cesium and strontium removed over a 5 months period was reported at 36% and 44%, respectively [96].

Benefits: Benefits associated with switchgrass are numerous. Planting switchgrass, even as a monoculture, is expected to enhance prairie biodiversity by providing forage, habitat, cover, and nesting areas for a diverse prairie wildlife that includes mammals, birds, amphibians, reptiles, invertebrates, and insects. Hohenstein and Wright [97] estimated a 95% reduction in soil erosion rates and a 90% reduction in pesticide use for herbaceous energy crops such as switchgrass relative to annual row crops like corn and soybean. It is also suitable for short windbreak plantings in truck farm fields [98] and it has been shown to improve water and soil quality by reducing carbon emissions through carbon sequestration [99]. Switchgrass can be easily integrated into existing farming operations because conventional equipment for seeding, crop management, and harvesting can be used [100].

Future directions: A significant amount of knowledge of the biology and agronomy of switchgrass has accumulated over the years through research on switchgrass as forage and recently as a biomass feedstock. There is now an understanding of the adaptation of existing cultivars and the development of new cultivars with improved yield and adaptation ability for different agro-ecoregions. However, there are still constraints that limit the use of switchgrass as a bioenergy crop. Problems with seed dormancy, improper or nonuniform planting depth, lack of weed control

options at establishment, and variable weather and soil conditions precluded the development of reliable and economic establishment methods [101]. A better understanding of how nitrogen is used and recycled in switchgrass under different growing conditions will help to develop fertilizer guidance and nutrient management specific to sites and soils [102]. Current research on the genetics, breeding, and molecular biology of switchgrass will result in new switchgrass cultivars with improved yield, greater establishment ability, and altered cell-wall properties for more efficient conversion.

Woody Biomass Crops

Introduction

Biomass, especially woody biomass and energy crops, already contribute substantially to cover energy demands around the world. Dedicated woody crops for biofuels have the potential to be an important energy source and will contribute to the substitution for fossil fuel energy [103]. In fact, the US Department of Energy has a vision to replace 30% of the liquid petroleum fuel for transportation with biofuels and similarly, the European Union Directive 2003/30/EC has targeted 5.75% of all petrol and diesel transport fuels to be derived from biomass by December 2010 [104]. Clearly, a multifaceted approach that includes both agricultural crops and dedicated woody crops will be necessary to attain these goals.

The principal challenge for biomass production is to develop and grow crops with improved physical and chemical traits while increasing biomass yields. Woody perennial plants like trees and shrubs grown for biofuels have the potential to play a central role in providing a renewable source of biomass for conversion to fuels while also providing a wide array of conservation benefits and ecological services, such as favorable habitat for wildlife, clean surface and ground water, conservation of soil and species diversity, that will exceed those associated with conventional annual crops [105].

Poplar

Origin and distribution: Hybrid poplars (*Populus* spp.) are among the fastest-growing trees in North America

and among the oldest types of dicotyledonous plants. The genus *Populus* consists of close to 35 species of deciduous flowering plants in the family *Salicaceae*, native to most of the Northern Hemisphere. It includes the cottonwoods, poplars, and aspens, all of which are sometimes termed poplars. The hybrids themselves represent crosses among various cottonwood species [106].

Cottonwood (*Populus deltoides*) was first introduced by early French explorers in North America, which crossed naturally with Black Poplar (*Populus nigra*), creating what is referred to as *Populus* × *euramericana* hybrids (<http://www.ag.ndsu.edu>). They were first cultivated around fields as windbreaks and were selected for fast-growing characteristics. In 1912, hand-pollinated poplar hybrids were produced in Britain. The shortage of timber after World War II spurred an increase in hybrid poplar plantations in Europe. Even though some of these European varieties were reintroduced to North America in the early 1920s, it was not until the 1970s that commercial planting of hybrid poplar started in the USA. Since then, a national consortium involving government researchers from several agencies, universities, and the private sector has been working on improving hybrid poplar. Research in this area is targeting reduction of production costs by targeting pest and disease resistance, increasing yields and improving management systems. Also, studies are being performed to establish the environmental impact of producing hybrid poplar [107] (<http://bioenergy.ornl.gov/main.aspx>).

Physiology: Poplars are deciduous trees with alternate leaves, furnished with the appendages known as “stipules.” Their flowers are dioecious; the calyx and corolla are replaced by simple scales. The female flower consists of a solitary one-chambered ovary, containing many ovules. Flowers are borne in long, sessile (attached directly to the stem) or pedunculated (growing from a stalk) aments, which are produced from buds formed in the axils of the leaves of the previous year. Leaves are green to dark green and measure 5–12 cm. The fruit is a two- to four-valved capsule, ripening before the full development of the leaf. The seed is light brown and surrounded by a tuft of long, soft, white hairs. Poplars can grow from anywhere between 15 to 50 m, with trunks of up to 2.5 m in diameter. They grow upright, with spreading branches

and their root system is shallow and wide-spreading, equal or greater than the height of the tree (Fig. 3). *Populus* species are somewhat susceptible to insects and diseases. Common diseases may include *Melampsora* leaf rust, *Septoria* leaf spot and canker, *Cytospora* canker, wetwood, and stem decay. Common insect pests include poplar borer, aphids, poplar bud gall mite, poplar vagabond aphid, and poplar leaf beetles (<http://www.2020site.org/trees/poplar.html>).

Culture: Hybrid poplar is a short-rotation woody crop (SRWC). SRWC's are species that usually are planted and harvested in less than 15 years [108]. Hybrid poplar stands are typically planted at 750–1,700 trees ha⁻¹ and allowed to grow for 6–12 years before harvest. Hybrid poplars are capable of resprouting from their rootstocks after harvest but it is recommended to reestablish the cultures to reduce the potential of diseases and also to exploit the new improved hybrid varieties. For the production of hybrid poplars, clay loams or sandy-loam, slightly alkaline (pH 5 to 7.5) and medium-textured soils are

recommended. They require a moist site and will not tolerate drought on upland sites. The use of herbicides or manual weed removal must be used in the first 3 years, but this is no longer necessary when the canopy closes, creating its own weed control. Furthermore, fertilizer applications are only necessary if the nitrogen level in leaves falls below 3% on a dry weight basis (<http://www.ag.ndsu.edu>, [107]).

Yield: Hybrid poplars, when grown under short-rotation silviculture, can produce between 8 and 22 Mg ha⁻¹ per year and achieve a height of 20 m in as little as 6 years. Average yields in the USA and range of yields by geographic region on hectares currently planted are shown in Table 7 [109].

Hybrid poplar growth and biomass yield could vary greatly depending on the site, the soil properties and weather conditions, as well as the species genotype. The above-ground biomass yield of 4-year-old hybrid poplar stands in Europe (in short-rotation coppice culture) and north central USA averaged between 2 and 11 Mg ha⁻¹ per year. In comparison, a recent study at the University of Saskatchewan reported growth and yield data in western Canada of 4-year-old Walker hybrid poplar stands from five locations to average from 0.17 to 0.19 Mg ha⁻¹ per year [110]. It has been suggested that once the crop is established, the combination of precipitation and temperature and its



Biomass Crops for Biofuels and Bio-based Products.
Figure 3
Hybrid poplar grove

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Table 7 Hybrid poplar yields in regions of the USA [109]

Region	Hybrid poplar yields	
	Average Mg ha ⁻¹ per year	Range Mg ha ⁻¹ per year
Lake States	9.9	7.9–11.8
Corn Belt	10.4	8.4–11.7
Southeast	10.1	8.6–11.7
Appalachia	8.0	9.0–11.7
North Plains	8.6	7.3–9.7
South Plains	8.4	7.3–9.0
Northeast	9.0	7.7–10.0
Pacific Northwest	12.9	12.4–13.5

influence on soil moisture becomes the most limiting factor for maximizing biomass production [111].

Advantages: Many advantages can be linked to growing hybrid poplars, from its positive effect on the environment to the fact that they are expected to be grown on agricultural cropland using standard production methods, thus reducing the need for new technology. Environmental benefits are linked to hybrid poplar's perennial nature. Chemical and fertilizer applications are considerably lower and these trees can intercept run-off nutrients to rivers and wetlands close by. Also, wind and water erosion over the life of the rotation is inferior to the erosion caused by annual crops and there is a clear ecological benefit of year-round trees for birds and habitat for small mammals. Their buds provide a source of food for birds, and their twigs and young branches make good forage for wildlife (<http://www.ag.ndsu.edu>, [107]).

The use of SRWCs for bioenergy production could substantially decrease the overall use of fossil fuels for energy. It would reduce CO₂ emissions into the atmosphere, increase soil organic carbon sequestration, and improve soil erosion control. Additionally, growing woody species like poplar on waste disposal sites and agriculturally marginal lands would definitely benefit rural communities [110].

Uses: Hybrid poplars are grown on plantations mainly for pulpwood used in the manufacture of paper. This wood is also sold as inexpensive hardwood timber, used for pallets and cheap plywood [106]. Wood and wood-derived fuels are a primary energy source in developing countries' domestic households as well as industrial facilities. From a medical point of view, *Populus* species can be a source of salicin, used for fevers and headaches. (<http://www.ag.ndsu.edu>, [107, 112]). More importantly, they are well suited for the production of bioenergy (e.g., heat, power, transportation fuels) and other bio-based products (e.g., organic chemicals, adhesives).

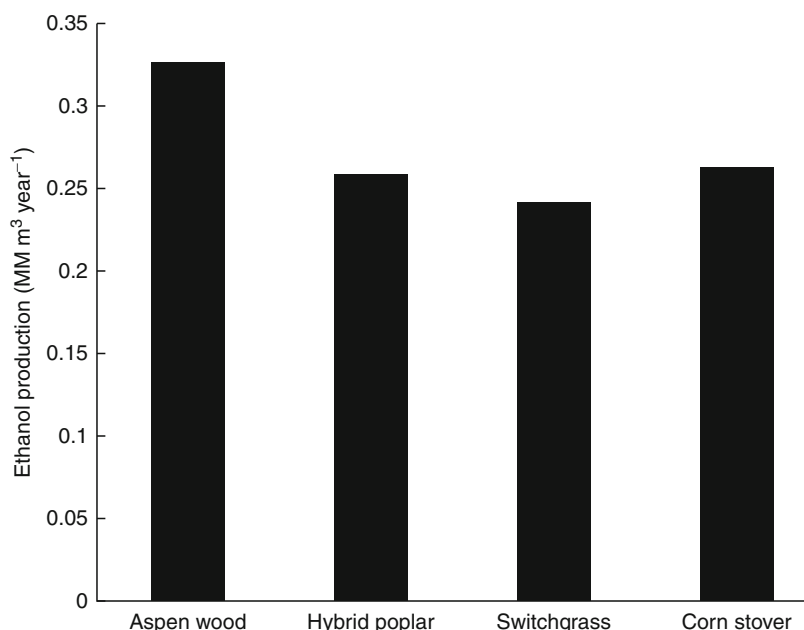
Poplar as a source of biofuels: Bioethanol is traditionally produced by converting either starch from grains such as corn, or sugar from sugarcane into ethanol. A second technology is based on the hydrolysis of cellulose or lignocelluloses into sugars, followed by fermentation to produce fuel ethanol [113]. The cellulose comes from woody parts of plants or trees, such as hybrid poplar and other short rotation woody crops.

The main objective in the production of ethanol from cellulose is to obtain a maximum biomass output with a minimum input. Developing new poplar varieties could expand the biofuel production without incurring the type of environmental problems that intensive agriculture can generate [114]. Major improvements have been achieved through breeding and genetic selection.

Poplars are the first tree for which the entire genome has been sequenced. Its 45,000 genes are being investigated to find ways to improve this tree, from genes that regulate its root system, improving water and nitrogen absorption, to cell wall modification for more extractable cellulose [115, 116]. New varieties focusing on more efficient roots not only would result in higher tolerance to drought but also in bigger trees and thus more biomass for the biofuels industry [115]. Alternatively, modification of cell wall polymers, such as lignin, which interfere with the enzymes needed to degrade cellulose, can benefit the extraction of cellulose from poplar trees for the production of ethanol [116].

To increase vigor and yield of poplar species, new crosses are being performed and examples of studies on new varieties are easy to find. Among these, a cross is found between *Populus trichocarpa* and *Populus deltoides* which has achieved a hybrid with leaves about four times as large as the leaves of either parent at a similar age, expanding their photosynthetic surface area. Other projects are looking at the biochemical indicators for drought tolerance in these hybrids, by growing them with or without irrigation and characterizing biochemical changes. All efforts are focused on fast-growing highly adapted poplar clones [106].

Up to now, traditional row crops like corn have been utilized for ethanol production. Several corn-to-ethanol plants are commercially in use around the world and it is known that they offer an alternative green energy source while minimizing greenhouse gas (GHG) emissions [117]. Nonetheless, poplar trees might have several additional benefits. In fact, corn ethanol reduces GHG emissions by about 13%, while cellulosic ethanol could greatly reduce GHG by 88% [118]. Even though wood from hybrid poplar can produce roughly the same ethanol production per unit biomass (Fig. 4), hybrid poplar generates 40% more excess electrical energy than corn. In addition, fast-growing cellulosic energy crops such as hybrid



Biomass Crops for Biofuels and Bio-based Products. Figure 4

Comparison of ethanol production utilizing aspen, hybrid poplar, switchgrass, or corn stover

poplar can be grown on a variety of land types, without having to compete with cropland for food and feed needs, as it is necessary for crops such as corn [117]. Poplar plantations do not require intensive inputs and are not harvested every year. There is a wide range of varieties and they could be grown in an equally wide range of climates, from subtropics in Florida to sub-alpine areas in Alaska. It should not be forgotten that the machinery necessary for poplar growth already exists and the infrastructure to handle the trees is already available [116].

The use of dedicated energy crops, such as hybrid poplars will not only address energy security issues, but will also inevitably be beneficial for the environment while addressing global climate change and economic development.

Eucalyptus

Origin and distribution: *Eucalyptus* is indigenous to Australia, Indonesia, and Papua New Guinea. There are more than 700 species of *Eucalyptus*, almost all (except for two) are native to Australia [119]. Species of *Eucalyptus*, prized globally for excellence in paper and energy production, are cultivated throughout

the tropics and subtropics in more than 90 countries worldwide representing 8% of all planted forests (FAO, <http://ftp.fao.org/docrep/fao/008/A0400E/A0400400.pdf>). A few cold-tolerant species and their hybrids grow in the temperate regions of Europe, New Zealand, and South and North America. The global land area under *Eucalyptus* cultivation is estimated at over 20 million hectares and Brazil has emerged as the major global producer and exporter of *Eucalyptus* wood with approximately 4.2 million hectares on plantations followed by India and China with ~3.5 million hectares and 2.9 million hectares, respectively [120]. *Eucalyptus* was first introduced to California as an ornamental plant in 1853. Soon after, it was widely planted throughout the state because it was fast growing and a renewable source of timber and fuel [121]. Its popularity was later replaced with the criticism that *Eucalyptus* forests compete with native plants and do not support native animals. Eucalypt forests in some parts of California were eventually removed [122]. The fuel crisis in the 1970s brought back *Eucalyptus* species as prime candidates for woody biomass cultivated on experimental farms mainly in central California. Two other places in the USA where *Eucalyptus* short-rotation research projects are conducted are located in

Hawaii and Florida [123, 124]. Other regions in the USA considered highly suitable for growing *Eucalyptus* are in Texas, Louisiana, and Georgia. Only four *Eucalyptus* species, *E. grandis* (EG), *E. urophylla* (EU), *E. camaldulensis*, and *E. globulus*, and their hybrids account for nearly 80% of the eucalypt plantations worldwide with *E. grandis* being the most widely used species in tropical and subtropical areas while *E. globulus* is the premier species for temperate zone plantations [125]. *E. grandis* is also used as a parental species in hybrid breeding and is rated worldwide as one of the fastest growing species and has the widest adaptability of all *Eucalyptus* species [125]. The greatest area of plantations of EG and its hybrids with other species are in Brazil and several other Central and South American countries.

Importance: *Eucalyptus* species are fast-growing woody perennials with many uses making them economically important trees. Eucalypts are commonly cultivated for the paper and pulp industries because of their high fiber yields and use as fuelwoods. In many poor countries in Africa [126], South America [127], and Asia [128] eucalypts are grown as a cash crop. *Eucalyptus* woods are used as mine props, poles, firewood, and charcoal [119]. The nonwood products derived from eucalypts include essential oils, honey made by bees from its flowers, and tannin [129]. The potential of *Eucalyptus* as a biomass feedstock for cellulosic ethanol has drawn attention to this species of woody perennial. The US Department of Energy (DOE) identified *Eucalyptus* as one of the crops with the potential to contribute to the biomass needed for biofuel to reduce the nation's dependence on imported fossil fuels [1]. *Eucalyptus* has many attributes and advantages that make it suitable as a dedicated energy crop. As a perennial, *Eucalyptus* can be cultivated under the coppice system. The cut stumps resprout to provide another crop. The retained roots with stored carbohydrates and access to soil water and nutrients help sustain rapid regrowth rates [130]. The tree withdraws the mineral nutrients into its roots at the end of a growing season, thus reducing the amount of fertilizer needed and thereby reducing the fertilizer costs and minimizing water pollution caused by run-off. The fact that harvesting only once every few years over a period of 15–20 years reduces the environmental impact created by disturbances at harvesting and planting (soil erosion

and nutrient loss) and saves on the cost of establishment (site preparation, seedling, and planting costs). *Eucalyptus* is one of the fastest growing hardwoods which grows well even on environmentally harsh lands (infertile soils, arid lands) [131]. It is a low input crop requiring minimum fertilizer and precipitation. *Eucalyptus* is also the world's most widely planted hardwood species that has multiple end uses, including feedstock for traditional forest products and energy products such as cellulosic ethanol and power generation through direct firing, co-firing or wood pellets in short rotation. In regions of the USA where *Eucalyptus* will most likely be cultivated, infrastructure already exists for planting, harvesting, handling, and processing wood for pulp that could also support the production, processing, and distribution of *Eucalyptus* crops. Last but not least, *Eucalyptus* species have been grown in the USA for many decades and have not demonstrated any invasive characteristics.

Growing conditions: Eucalypts are hardy trees and the majority of *Eucalyptus* species will grow in a range of soils from pH 4.5 to 8.5. They do not require fertile soils and many species naturally occur in shallow, low fertility soils. When grown on deeper more fertile soils they generally grow faster, bigger, and more luxuriant. Some species do require good drainage while others will grow on heavy clay and even on boggy, partially waterlogged sites. Several species grow well on high pH soils, and most species adapt to higher pH soils, although usually with reduced growth rates. *Eucalyptus* will tolerate an annual rainfall of 500–5,000 mm and an annual temperature of 12.3–27.9°C (Table 8). *Eucalyptus* is considered one of the most adaptable plant genres, and the trees are remarkably hardy in all kinds of weather conditions. Once established the mature trees adapt to the local growing conditions and become very tolerant to drought and prolonged dry periods. However, the young trees of most *Eucalyptus* species do not tolerate frost very well and will succumb to extreme fluctuation of temperatures [132]. Fertilization and nutritional studies of *Eucalyptus* spp. in Australia, Brazil, and Hawaii pointed to a general need for supplementary nitrogen, and sometimes phosphorus, especially at planting and soon thereafter [133, 134]. Fertilizer (N-P-K) is generally applied at planting and again about 6 months later. Subsequently, only nitrogen is needed on most sites. The total amount

Biomass Crops for Biofuels and Bio-based Products. Table 8 Growth requirements of *Eucalyptus* species in USA

Growth requirements	<i>E. grandis</i>	<i>E. saligna</i>	<i>E. camaldulensis</i>	<i>E. globulus</i>
Adapted to coarse textured soils	Yes	Yes	Yes	Yes
Adapted to fine textured soils	Yes	No	Yes	Yes
Adapted to medium Textured soils	Yes	Yes	Yes	Yes
Drought tolerance	Low	Medium	Medium	Low
Fertility requirement	Medium	Low	Low	Medium
Frost free days, minimum	340	340	180	240
Moisture USE	Medium	Medium	High	High
pH, minimum	4.0	4.0	5.0	5.0
pH, maximum	6.0	6.0	8.5	6.8
Planting density per acre, minimum	170	170	170	170
Planting density per acre, maximum	1,200	1,200	1,200	1,200
Precipitation, minimum, (mm)	1,016	1,524	508	553.4
Precipitation, maximum, (mm)	1,778	5,080	2,540	1,524
Temperature, minimum (°C)	2–2.2	–6.1°C	–8.3°C	–8.3°C
Coppice potential	Yes	Yes	Yes	Yes
Resprout ability	Yes	Yes	Yes	Yes

(Source: <http://www.plants.usda.gov>)

required depends on the nitrogen status of the topsoil and may range from 224–673 kg ha⁻¹ in four to eight applications (depending on the site quality and rotation length) [123]. The application of nitrogen may be eliminated or reduced with the practice of intercropping with nitrogen-fixing species such as *Leucena* or *Albizia*. Such practices were studied in Hawaii [135], Brazil [136], and India [137] and have shown that it is possible to maintain both the yields and nitrogen status of the soils without using nitrogen fertilizers, or with much reduced fertilizer inputs. *Eucalyptus* can be planted at any time of the year in tropical and subtropical areas but spring time is recommended for colder regions. Young *Eucalyptus* trees do not compete well with weeds; therefore, weed control in the early stages of establishment is very important in the management of *Eucalyptus* cultivation. Weed control is carried out before planting the trees and during the first 2 years of establishment. Pre-emergence and post-emergence herbicides found safe and efficacious for *Eucalyptus* are listed in a report by Elmore [138]. The

projected rotation age for bioenergy production is 5 years under optimum growing conditions and a year or two longer under less favorable conditions [125]. However, new and high-yielding varieties have the potential to reduce rotation length to 4 years or less [139].

Yield: The yield of *Eucalyptus* biomass varies widely from species to species and also with provenances (place of seed origin), sites, and management systems around the world. Small plot studies conducted at the University of Massey, New Zealand, comparing the yields of 19 *Eucalyptus* species grown under similar conditions and managed under a coppice regime highlighted the differences in survival rates, the number of shoots per tree, the shoot/tree sizes and ultimately the yields between different species. The yields obtained vary from 4 to 20 Mg ha⁻¹ per year and only six species: *E. brookerana*, *E. botryoides*, *E. botryoides* × *saligna*, *E. ovata*, *E. elata*, and *E. oblique* had yields averaging 16 Mg ha⁻¹ per year [140]. The yield evaluation of *Eucalyptus* species in small plot trials in Hawaii

Biomass Crops for Biofuels and Bio-based Products. Table 9 *Eucalyptus* biomass yields at five Hawaiian sites after 5 years [141]

Site/Island	Tree species	Elevation (m)	Annual rainfall (mm)	Average temperature (°C)	Agronomic conditions	Planted density (trees/ha)	Annual yield (Mg ha ⁻¹ per year)
Mountain View, Hawaii	<i>E. grandis</i>	296.3	4,623	21.1	Wet, upland	405	20.16
	<i>E. saligna</i>					405	11.2
	<i>E. urophylla</i>					405	20.16
Honokaa, Hawaii	<i>E. grandis</i>	232.3	2,057	21.1	Moderately dry, upland	405	29.12
	<i>E. saligna</i>					405	20.60
	<i>E. urophylla</i>					405	31.80
Puunene, Maui	<i>E. grandis</i>	7.6	483	25.0	Dry, irrigated, lowland	485	16.57
Kilohana, Kauai	<i>E. grandis</i>	256.6	3,023	20.6	Wet, intermediate elevation	405	16.35
	<i>E. urophylla</i>					405	17.47
Hoolehua, Molokai	<i>E. camaldulensis</i>	76.2	711	22.8	Dry, irrigated, intermediate elevation	405	9.85

emphasized the suitability of sites and species (Table 9). *E. grandis* and *E. urophylla* are relatively highly productive at a higher elevation with moderate to high precipitation but not at a lower elevation. *E. camaldulensis* performed poorly at low elevation even with irrigation. *E. urophylla* has the highest annual yield with ~35 Mg ha⁻¹ per year at the moderately upland site [141]. The importance of provenance selection for different sites was brought out in the data for *E. camaldulensis* planted in Afaka, Nigeria. Five-year-old trees had a mean annual increment (MAI) that ranged from 17.3 to 5.1 Mg ha⁻¹ per year depending on where in Australia the seed had come from. This demonstrates a possible threefold increase in yield achieved simply by selecting a seed source location [131].

A well-managed *Eucalyptus* plantation will improve the performance of the crop and will maintain a relatively high level of yield throughout the coppice regime. *Eucalyptus* cultivated with irrigation and fertilizer gives a higher yield over *Eucalyptus* grown without these additions. This was demonstrated in a pilot experiment

in Brazil under the Brazil *Eucalyptus* Potential Productivity Project (BEPP). The yields of *Eucalyptus* cultivated with no fertilization were 28% lower than yields achieved with fertilization, and the response to irrigation was found to be far larger than that of fertilization. The growth increase from irrigation ranged from a low of 7% at the cooler, higher elevation site to 67% at the driest site [142]. The stand uniformity also has an influence on the yield. Stands with uniform structure (trees in plots planted in a single day) showed 13% greater growth than stands with higher heterogeneity of tree sizes (owing to staggered planting). The yields reported 2 decades ago in field trials in California, Florida, and Hawaii were typically 20–24 Mg ha⁻¹ per year [124, 141]. Over the last 10–20 years of intensive research, improved silviculture (site preparation, fertilization and weed control) and superior clones have improved yields, exceeding 37 Mg ha⁻¹ per year with the potential to reach ~66 Mg ha⁻¹ per year [124]. In Brazil, commonly planted *Eucalyptus* hybrids such as *E. grandis* × *E. urophylla* routinely yield ~24–30 Mg ha⁻¹

per year [142]. Large gains in yield can be achieved by the careful selection of species, sites, provenances, and management system to suit the local conditions.

Economics: Growing biomass and producing bioenergy require a substantial financial investment. Hard numbers on the economics of growing *Eucalyptus* for bioenergy on a commercial scale are unavailable. However, the cost projection from small plot trials in Hawaii for producing and delivering biomass feedstock to the central facility, excluding storage, processing, and biomass conversion ranges from US\$30 to US\$100 per dry Mg [143]. The estimated cost of producing and delivering *Eucalyptus* in the southern USA ranges from US\$50 to US\$60 per dry Mg, based on a yield of 28–16.8 Mg ha⁻¹ and on a delivery range within 48 Km of the processing site [144]. Factors that contribute to the cost of production are establishment, maintenance, harvesting, transportation, rotation length, and productivity. The cost can be greatly reduced by growing highly productive species, having higher tree stand density and a shorter rotation length. The economic feasibility of growing *Eucalyptus* for biomass can be improved by increasing productivity through improved germplasm, an efficient management system, and improvements in biotechnology. Introducing traits such as improved growth, stress tolerance, reduced lignin composition for easier processing of the biomass, and improved wood quality through increasing cellulose composition will increase productivity and add value to the crop.

Conclusions and Future Directions

Agricultural residues: Residues can contribute as much as 428 million dry Mg per year to biomass harvests for conversion to transportation fuels. Nevertheless, it is clear that although there is a positive energy balance from residue utilization, many factors other than ethanol output have an impact on the use of these residues. Maintenance of soil fertility is paramount to the sustainability of this biomass source. Compensation for the farmer is highly important as well, with potential of their participation in farmer cooperatives (co-op's) to capture part of the value chain and ensure their continued involvement. Additionally, harvest and storage logistics must be explored and resolved. Handling large quantities of loosely packed biomass, transporting it

over long distances and storing it in bales or wet stacks are only a few of the logistics issues. Harvesting activities must be coordinated so that the process of grain collection and storage is not slowed with resultant loss in their valuable revenues. However, the potential of this biomass source is important enough for the investments necessary to make these residues a feasible feedstock.

Sweet sorghum and sugar cane: Sugar cane and sweet sorghum are members of same family and share physiological characteristics. Their use as bioenergy crops is almost identical. For the last 40 years, sugar cane has been used as a bioenergy crop in Brazil, which is a successful example of a country that has reduced its gasoline usage by producing bioenergy. Sweet sorghum is considered to be one of the most drought-resistant agricultural crops as it has the ability of remaining dormant during the drought period. de Vries et al. [145] analyzed different biofuel production systems in geographical regions where they are currently important for ethanol. Among the six “first generation” biomass crops, e.g., maize (USA), wheat (Northwest Europe), sugar beet (Northwest Europe), cassava (Thailand), sweet sorghum (China), and sugar cane (Brazil), biofuel production from sugar cane and sweet sorghum delivers substantially more energy per unit energy spent than from the other crops. These two C4 sugar-producing plants appeared to be most sustainable and most efficient in the use of land, water, nitrogen, and energy resources, while pesticide applications were relatively low in relation to the net energy produced. An agronomic and yield comparison of sugar cane and sweet sorghum is presented in Table 10.

Both sugar cane and sweet sorghum are excellent feed stock for first-generation bioethanol production. However, in order to reduce the usage of fossil fuel and attain the goal of sustainability, utilization of lignocellulosic biomass for the production of cellulosic ethanol plays a vital role. Lignocellulosic-rich bagasse from sugar cane and sweet sorghum has the most positive net energy balance among the common feedstocks potentially used for bioethanol production. Sugar cane and sweet sorghum have comparable energy balance, with 8.3 and 8 units of energy produced for every unit of energy invested in their cultivation and production, respectively, especially when compared with 1.8 units for corn grain. On the other hand, only 0.8 unit of

Biomass Crops for Biofuels and Bio-based Products.**Table 10** Comparison of sugar cane and sweet sorghum [146]

	Sugar cane	Sweet sorghum
Crop duration	About 7 months	About 4 months
Growing season	Only one season	One season in temperate and two or three seasons in tropical area
Soil requirement	Grows well in drain soil	All types of drained soil
Water management	36,000 m ³ h ⁻¹	12,000 m ³ h ⁻¹
Crop management	Requires good management	Little fertilizer required; less pest and disease complex; easy management
Yield (ha ⁻¹)	70–80 Mg	54–69 Mg
Sugar content on weight basis	10–12%	7–12%.
Sugar yield	7–8 Mg ha ⁻¹	6–8 Mg ha ⁻¹
Ethanol production directly from juice	3,000–5,000 L ha ⁻¹	3,000 L ha ⁻¹
Harvesting	Mechanical harvested	Very simple; both manual and through mechanical harvested

energy is produced in fossil fuel production for every unit invested [147]. Currently eight times more energy is produced from sugar cane than what is used in its creation. When bagasse is included in the equation, it is estimated that the number may increase to as much as 16 times. Bagasse is the feedstock with the most positive energy balance available in the near term. Sugar cane bagasse shows significant potential for making the biomass-based ethanol an economically viable solution.

Switchgrass and Miscanthus: Perennial grasses are nonfood crops which can yield high-quality materials for both energy and fiber production. Switchgrass and *Miscanthus* are immense biomass producers and show great potential as bioenergy crops. They can be grown

over a wide range of conditions and with minimal agricultural inputs. Switchgrass has deep roots that makes it less susceptible to drought stress and enables it to adapt better in areas where the water precipitation is lower than that required by *M. × giganteus*. An analysis of published yields indicates *M. × giganteus* produces more biomass per unit area and per unit input than switchgrass but the yields of *M. × giganteus* are more strongly influenced by water, while those of switchgrass are more strongly controlled by nitrogen [43]. Therefore, in locations with ample rainfall but with concern over nitrogen contamination of water supplies, it may be better to grow *M. × giganteus* while conversely, in arid areas without contamination concerns, greater yields may be obtained growing switchgrass as long as adequate nitrogen fertilization is provided.

Woody crops: Woody crops such as Poplar and *Eucalyptus* represent a critical component of the bioenergy future. They have the potential to be a significant part of the bioenergy solution in the USA and in many other parts of the world. In the USA, perennial woody crops are expected to account for part of the 377 million dry Mg of the 1.37 billion dry Mg total biomass resource potential. The projected yield for the long-term feasibility of renewable energy production defined by DOE is 20 Mg ha⁻¹ per year [1]. The projected yield is not only achievable but can be exceeded with improved silviculture, the use of superior clones, and genetic improvement. Investments in research and technology are needed to improve productivity and bring down the cost of production. Recent advances in genetically modified *Eucalyptus* include a freeze-tolerant variety and a low-lignin and high-cellulose variety. The freeze-tolerant variety was developed using a highly productive tropical hybrid, *E. grandis* × *E. urophylla* [139]. A field test of the freeze-tolerant variety demonstrated its ability to maintain its productivity even at temperature as low as −9°C. This has made possible commercial plantings of tropical *Eucalyptus* species in the Southeastern USA where cold winter temperatures would normally restrict such cultivation. The low-lignin and high-cellulose variety with 18% less lignin and 4.5% more cellulose developed by a team of Taiwanese and US scientists (China Post, 2007, <http://www.chinapost.com.tw/taiwan/2007/09/14/122524/Gene-modified-eucalyptus.htm>) would add value to

the crop by improving efficiency in the pretreatment step utilized in fermentation systems for biofuels production from lignocellulosic raw materials. The authors estimated that an output of 0.9 million Mg of this new variety could generate extra revenues of about US\$36 million every year. Advances in research and technology in growing *Eucalyptus* in Brazil over the last 40 years have paid off significantly. Productivity of *Eucalyptus* biomass has increased twofold to fivefold depending on the site quality [148, 149]. Improved new varieties of poplar trees are currently being obtained through genetic engineering and breeding. Varieties with larger leaves, improved root system, and modified lignin are associated not only with higher biomass yields and better net energy balance but they would definitely have a lower environmental impact [115, 116].

Growing *Eucalyptus* and hybrid poplar for biomass is sustainable and will be economically feasible with improved varieties and technology. The use of woody crops for bioenergy offers many benefits with no anticipated long-term environmental impact and may be part of a long-term solution to the nation's energy security.

In order to ensure feedstock availability whether from dedicated crops or from residues, changes in farm and energy policies will need to be made, making sure they are connected to incentivize this new industry.

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Biomass Energy Heat Provision for Cooking and Heating in Developing Countries

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Article Outline

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Glossary

Biomass Biomass is defined as material of biological origin excluding material embedded in geological formations and/or transformed to fossil.

DALY Disability-adjusted life years or DALYs, a measure combining years of life lost due to disability and death.

GIS Geographic Information System which embodies a spatial data base and mapping capability.

GWP Global warming potential, a measure in carbon dioxide equivalent terms of the climate change potential of different compounds in the atmosphere.

HHV Higher heating value or Gross Heating Value (GCV), the energy released on complete combustion including the latent heat of the condensation of water produced in the combustion.

IEA International Energy Agency, a body of the OECD (Organization for Economic Co-operation and Development).

ICS Improved cookstove – a range of technical innovations to improve efficiency and mitigate emissions in an affordable package.

Lambda Symbol λ = mass of air supplied/mass of air required for complete combustion to water and carbon dioxide.

LHV Lower heat of combustion – see HHV, the difference is that the LHV does not include the latent heat of condensation.

LPG Liquefied petroleum gas customarily propane and or butane.

MDG Millennium development goals of the United Nations, an ambitious set of targets for human development of the poorest people in the world.

NMHC Non-methane hydrocarbons or sometimes.

NMVOC Non-methane volatile organic carbon.

PIC Products of Incomplete Combustion which include reactive organic molecules and carbon monoxide, as well as unburnt carbon, which is a particulate often called soot.

WBT Water boiling test, a widely agreed upon laboratory protocol to measure the efficiency of cookstoves under standardized conditions.

Definition of the Subject

Biomass cookstoves are at the nexus of food and energy poverty in developing countries. Superficially, biomass-fueled cookstoves are simple objects that contain a fire and transfer energy to a surface or vessel in which food can be cooked and water boiled. However, the simplicity is illusory because just as in industrial economies the energy needed to service the food chain from farm or garden, to fork or chopstick, is a large and significant burden on the household economy especially in poorer households. This burden is not just economic, but impacts social, humanitarian, and equity issues that directly affect the lives of more than one third of humanity, and impact on the global environment, via the link with climate change gas emissions.

The key challenge is that very low cost biomass-fueled small appliances are an unsatisfactory technology for efficient and nonpolluting combustion. Over 70 years ago the move to improve stoves started in India, with one of the first to reach national distribution being the Magan Chula with a mud and pottery mix construction [1] developed in 1947 by the All India Village Industrial Association (AIVIA), Maganwadi. AIVIA was initiated by Gandhi to further rural

development in India [2]. The development was in a context of providing employment opportunity for potters as well as to improve the lives of women through efficiency and cleanliness improvements of biomass-fueled stoves in the kitchen. A similar ethos of multiple objectives is behind the recently announced public-private initiative “Global Alliance for Clean Cookstoves” coordinated by the UN Foundation [3] with the goal of “save lives, improve livelihoods, empower women, and combat climate change by creating a thriving global market for clean and efficient household cooking solutions.”

This entry explores the technology background to these issues and the possibility of their amelioration.

Introduction

In the OECD countries, the logistics chain from the farm gate to the fork on the table is a major component of the economy and the energy system. Agriculture itself is a major consumer of energy, but surprisingly it is in the post-harvest system that there is a larger consumption of energy. This is found in the chain: food processing and brand marketing (processing); food and ingredient packaging (packaging); freight services (transportation); wholesale and retail trade and marketing services (wholesale/retail); away-from-home food and marketing services (food service); and household food services (households). Using the national input-output tables exemplarily for the US economy the energy use in an industrial society from the farm to the table is about 15% of the total primary energy use [4]. Processing, food services, and households account for 60% of the food-related energy flows, while agriculture represents less than 15%. With 110 million households in 2002, the food-related energy consumption (after the farm gate) is almost 110 GJ per household. With an average household size of 2.6, the per capita usage is 42 GJ.

In the rural rice economies of Southeast Asia, with populations still preparing most of their food at home, food has its origins locally without the major packaging, transportation, and wholesale/retail components of the chain in industrialized countries, and this results in a food chain demand that is much less than that of industrialized countries. Absent Leontief style input-output tables for developing countries suggests that the

estimates that correspond to the US case are hard to obtain. A 90-country average of $4.1 \text{ GJ caput}^{-1}$ for the individual energy use in the post-harvest system was found in the middle of 1980s [5]. However, as would be expected the values varied widely by country with as low as 4 GJ caput^{-1} for Africa, and a high of $7.75 \text{ GJ caput}^{-1}$ in Latin America. By far, the largest share of energy in the post-harvest system in developing countries is in cooking – representing 85% in Africa, and only 61% in Latin America, with the average being 74%.

The large difference in the per capita energy consumption post harvest in developing countries versus that of the USA, and the very high proportion that is involved in household cooking serves to emphasize the critical role of cookstoves in development.

The developing country nexus of energy, nutrition, health, indoor and outside air pollution, and degradation of the environment has received considerable attention in the last 60 years. In India, the Magan Chula was a response to indoor air pollution though OECD country interest did not become significant until there were concerns of deforestation [6]. This was then followed by assessments of health, gender issues, social equity, and more recently the global warming potential of the emissions from biomass burning. The impact of these is very dependent on the number and quality of biomass cookstoves and the quantity of fuel that is used. Such data is very hard to obtain and the available estimates are a combination of survey data as well as model assumptions.

The International Energy Agency (IEA) estimates that about half of the population of developing countries, 2.5 billion people, relies on biomass in the form of fuelwood, agricultural residues, and animal dung, and the biofuel charcoal to meet their needs for cooking. In many countries, these fuels meet over 90% of household energy needs. These needs are primarily for cooking, followed by heating, and lighting. The developing country household energy use is estimated at 45 EJ y^{-1} , and the biomass demand is about 32 EJ . This is often described as traditional biomass use, in order to distinguish it from the approximately 15 EJ of “Combustible renewables and waste” an IEA classification that includes municipal solid waste, as well as biomass. The majority of this 15 EJ is used at high efficiency in

the heat, power generation, and industrial sectors of the developed economies [7, 8].

Despite the large amount of primary energy going to cookstoves, the efficiency of use is quite low compared with cooking either with natural gas or LPG. The IEA has carried out the thought experiment of replacing biomass cookstoves by LPG estimating that 1.3 billion people would require only 30 Mt of LPG or 1.5 EJ suggesting that replacement of all biomass in cooking by efficient fossil-fueled appliances would have a negligible effect on world fossil hydrocarbon consumption [8]. Another estimate by Goldemberg, quoted by [9], is that 2 billion people would need 120 million tons of oil equivalent or approximately 5 EJ . The efficiency of LPG stoves versus the three-stone stove system is about four times greater with minimal emissions other than carbon dioxide.

Another way to make this biomass fuel estimate is from the bottom up, working from the types of device, and their efficiencies. Cookstoves at the household scale typically have a steady state power output in the range of 1–3 kW, with peak outputs near to 10 kW. Institutions such as schools and hospitals, as well as food vendors and restaurants also use household scale stoves and larger units going up to 50 kW thermal output. The duty cycle for cookstoves ranges from one or two meals a day, say 3 h of usage total, in many households, to much longer for diets that include long cook cycles, as well as in institutional settings.

The estimates of the number of people dependent on solid fueled appliances vary widely. Especially as it has long been recognized that there is an economically driven energy stack [10], such that the poorest at the bottom of the stack will likely use only biomass, while a person much further up the economic ladder may still have a biomass-fueled stove, but will also use electricity, natural gas, LPG, or charcoal. In the business world, the energy stack would be described as a portfolio to reduce risk, since when there is no electricity, or the supply of LPG is unavailable, then there is biomass to fall back on. The World Bank considers that the number using biomass is three billion, with one billion almost totally dependent on biomass fuels [11].

If an average daily duty cycle of 4 h, and assuming a 2 kW output from a 10% efficient stove then with one billion people in an average household of four persons, the annual energy demand is 7.3 PWh or 26 EJ .

This value is of course a floor value for the impact, as many more people with presumably a lower duty cycle will also be using biomass. Thus, both bottom up assumptions and the combination of survey measurements and statistics arrive at a very similar value for the range of primary energy consumption by cookstoves 30–45 EJ.

The need for cooking is integral to the life of modern humans. Evolution over the last 200,000 years has taken the species *Homo*, from a diet of fruits and tubers, with some meat, to a diet in which for many meat is rare and cereals such as rice, corn, and wheat and starch staples such as potato and cassava are the primary source of metabolic energy [12]. Cooking is essential for the modern human to be able to access the energy of hard-to-digest foods, render them more palatable, eliminate toxins, and reduce microbiological risks [13, 14]. The extent or duration of cooking and the temperatures needed for different tasks such as boiling, simmering, frying, and baking unleavened bread are very diverse, and this is reflected in the range of stoves from the Plancha type used for maize foods such as tortillas, to the Chula type used primarily with water boiling and simmering applications.

It has been chosen not to illustrate this entry with any figures showing either the three-stone stove or the various ICS as it is more important to understand the behavior and dynamics of the cookstove as a class. There are literally hundreds of ICS in literature and a good selection of photographs and drawings (some with dimensions) are to be found within the references [1, 15, 16].

To make foods nutritious, the cooking times will also be an important determinant on the fuel consumption. An interesting study of the effect of altitude on the wood consumption when cooking beans highlights the importance of cooking time on the energy consumption in preparing cooked food [17].

Biomass Use in Stoves: Environmental Impacts

The environmental impact of the biomass stove sector ranges from local resource depletion, due to overconsumption, through to indoor and outdoor pollution. Indoor pollution is associated with a horrendous health impact mainly on women and children and is the

subject of a separate section, while external pollution has local, regional, and global impacts.

Biomass Resource Impacts

The primary issue is the balance between biomass growth and productivity, and the rate of consumption. The production of wood fuels is generally local and regional with only limited trade between regions on account of the large bulk and low energy density of solid wood. Other biomass fuels such as stalks and straws or dung have even lower energy densities. Local demands depend on population density and have seasonal variations. Access to the wood fuel resource will depend on the availability of land, proximity of woodland and forest, and their access rules. The latter will depend on the nature of the forest land, whether it is for wild life conservation, water catchment protection, and the timber production policies of the national and regional governments.

While there have been many popular press stories of deforestation attributed to fuelwood use – more empirical research has revealed a much more nuanced story with the number of users that are using wood and other biomass resources non-sustainably much less than anticipated. A partnership between the FAO Forest Products Service and the Ecosystem Research Center (CIECO) of the National University of Mexico (UNAM) has generated and tested a GIS based system for identifying and determining priority areas for intervention to support wood energy and bioenergy planning and policy formulation. The tool that was developed WISDOM (Woodfuel Integrated Supply/Demand Overview Mapping) [18] has been applied to Southeast Asia. In combination with poverty data, the tool enabled the identification of areas where poor rural and urban populations that depended primarily on wood fuels for their subsistence energy supply would be likely to suffer severe shortages thus allowing the appropriate poverty alleviation and energy development planning.

The Southeast Asia analysis [19] showed how difficult it is to generalize about both malnutrition and woodfuel; while in 2000 one quarter of the region's population, almost 66 million people live in concomitant conditions of poverty and wood fuel deficit, 35% are in areas of high to medium surplus wood fuels.

The most vulnerable countries in the region are Cambodia and Vietnam, while most other countries had only pockets of poverty and deficit – mostly those with better biomass resources as in Lao PDR, Malaysia, and Yunnan PRC.

Given the land use competition in many regions, there has been extensive research into wood species with characteristics suitable for combustion, with rapid growth and low nutrient requirements being desirable qualities [20, 21].

Much work has been done on the consumption side and in the historical evolution of cookstove development. The initial emphasis was on efficiency for the production of Improved Cookstoves (ICS) in relation to the perceived fuel wood shortages.

Cookstove Efficiencies and the Design of Improved Cookstoves (ICS)

The efficiency of biomass-fired cookstoves is low especially when compared with large scale solid fuel-fired industrial and power generation units.

What exactly is meant by efficiency? There are two stages in the chain from the biomass fuel to the cooked meal. The first stage is the generation of the heat from the chemical energy content of the fuel. The second stage is the transfer of this heat by convection, conduction, and/or radiation to the food or the container in which the food is being cooked. Each of these stages has potential and actual losses, which need to be minimized.

In the first stage, the key is to have complete combustion in which all of the carbon and available hydrogen contents of the fuel are converted to carbon dioxide and water, and all of the resulting energy is transferred to the heat carrier. Combustion of fuels containing carbon and hydrogen in air (oxygen) only takes place in the gas phase, and as will be seen this has serious consequences for how efficient the process will be. This means that solid and liquid fuels, such as wood and oil, have to produce fuel gases either by pyrolytic decomposition or volatilization for the combustion to take place. This is explained from the combustion of gaseous fuels to the combustion of solid fuels.

In the case of a gaseous fuel, the fuel and the air are premixed before going into the combustion chamber. Normally, this premixing will be realized at a specific

air to fuel ratio (expressed as λ , and defined as mass of air supplied/mass of air required for full combustion to water and carbon dioxide). Typically, the value of λ for a premixed fuel is less than unity. Such a premixed fuel is sometimes described as a rich fuel mixture when λ is below 1.0. Additional air is then supplied in the combustion chamber as secondary air to ensure combustion under conditions of excess air – at which point the combustion is lean with λ above 1.0. A typical gas flame in a domestic appliance is a laminar flow premixed flame in which after ignition, a flame front moves down toward the supply of premixed gas at a very high temperature – the flame is stabilized when it reaches the burner tip. Natural gas flames in air are usually transparent to blue in color, and the heat transfer from the flame is to the heated mass of combustion products that are diluted by the surrounding air. There is little or no radiative heat loss as the flame is not a black body. The chemistry in the flame provides energy to dissociate the fuel into free radicals, which then react with the oxygen in the air to provide heat. So long as the thermal energy provided by the free radical reaction with oxygen exceeds the energy needed to dissociate the fuel, the flame is stable.

When a liquid fuel is burnt, the situation is more complex as the liquid must now be evaporated and the fuel vapor mixed with air prior to ignition. The liquid fuel has to be well dispersed in the air as it evaporates to avoid local areas of fuel rich composition. So most pressurized liquid fuel burners at a small scale have a heated section that serves to evaporate the fuel. Thereafter, the flame is similar in concept to a gas flame. The alternative arrangement is to have a wick to draw the liquid fuel up to a heated area in which the fuel evaporates and is mixed with air to burn. In developing countries both pressurized and wick stoves are commonly fueled with kerosene, with serious safety impacts due to the large boiling point range and relatively low flashpoint of paraffinic fuels which are sometimes diluted with even more volatile gasoline [22].

Solid fuels such as coal and biomass in the form of wood, straw, or dried dung have to undergo an even more significant transformation. The solid fuel has to be heated to a point that it breaks down to generate fuel vapors and fuel gases. Then the flame has to provide heat continuously to the solid to continue generating the fuel that burns. Observation of open wood fires will

show that the flames are strongest when the faces of two burning logs are opposed to each other so that the radiative heat from the combustion is trapped between them. Conversely, if a flaming piece of wood is pulled from the fire, after a short while the flames will be extinguished and the wood will only smoulder producing copious amounts of noxious smoke. This challenge of maintaining a radiative heating environment to burn solid fuels either at a small scale or in an open fireplace has been known for a long time. When open fireplaces were common in the 1960s in the USA, patents to maintain logs in a triangular pitch configuration to enable this radiative trapping to encourage good combustion were quite common [23].

Ignition and combustion of solid fuels is complex, in part because very often the first process that has to take place is drying the material – if the fuel has moisture it has to be removed before the temperature can rise to the point where the solid will pyrolyze or break down with heat. Also not all of the wood or biomass is combustible, as it also contains chemical elements that appear after combustion as ash – typically the oxides of calcium, silicon, and aluminum, along with potassium and sodium. In the living biomass, these elements have played a major role in the growth process and some have been picked up from the soil as dust. In any case, they are inert and consume heat without producing fuel gases to burn.

The heating value of a fuel is measured as either the higher (sometimes called gross calorific value) heating value (HHV) or the lower heating value (LHV; i.e., net heating value). The difference between the two is the fate of the water produced in the combustion step. If it is condensed – as happens in the bomb calorimeter that is used to measure fuel energy content. The HHV is greater than the LHV by the heat of condensation of water. Normally combustion systems only yield the LHV energy, as there is no water condensation.

The heating values of fuels are given in Table 1. Here the large effect of water content between green firewood and the air dried versus the bone-dry wood can be seen. This emphasizes the need for dry fuels in biomass combustion. Moisture not only lowers the heating value, but also increases the lambda needed and reduces the maximum flame temperature.

More accurate values of biomass composition and heating values can be obtained from the database

Biomass Energy Heat Provision for Cooking and Heating in Developing Countries. Table 1 LHV of fuels on a mass basis

Fuel type	Heating value (LHV) MJ kg ⁻¹
Wet or “Green” firewood; 50–60% moisture	8
Cow dung – dried	10
Tree residues: twigs, leaves, forest duff, etc.	13
Agricultural residues: straws, stalks usually dry	13
Air dried firewood; 20% moisture	15
Densified briquettes: straw, rice husk, bagasse	16
Oven or “Bone” dried firewood; <10% moisture	20
Charcoal	28
Charcoaled briquettes	30
Kerosene	44
Biogas (55:45 methane: carbon dioxide volume)	16
LPG – liquid propane gas	46

Adapted from [24]

(<http://www.ecn.nl/phyllis>) which enables access to be made to different species, which have different heating values as a result of compositional differences. At the level of cookstove technology such differences will not be crucial in determining performance.

Combustion Principles and Their Application to Stoves

To get the highest efficiency out of a solid fuel requires that all of the chemical energy is realized by converting all of the carbon and available hydrogen into carbon dioxide and water. At a very large scale, such as industrial boilers, it is possible to construct the combustion section separate from the heat transfer section, even though they are closely coupled. The enclosed combustion section can also be carefully controlled with respect to the addition of air to achieve combustion with the minimum of excess air. It turns out that the

key variables to control are the temperature (T), the duration of the combustion (time = t), and efficient mixing of the air oxidant with the solid fuel derived flammable volatiles (turbulence = τ).

Temperature is very important since the rate of oxidation kinetics of the gaseous fuel species increase with temperature, while the higher temperatures feed-back heat by radiation to the solid fuel surfaces encouraging pyrolysis and cracking of the solid fuel, and increasing the rate of surface reactions. Thus, at its simplest, the temperature has to be very high, and under conditions of lambda close to unity, the adiabatic flame temperatures for biomass can be above 1,600°C. Such high temperatures are a challenge to many metals, with softening temperatures of mild steel occurring around 550°C despite a melting point of 1,525°C. Even stainless steel AISI 310 can only operate safely at 1,100°C under small strain. Thus, to maintain high temperatures, it is typical to have refractory lining in boilers and combustors to protect the structural steels used.

While ceramic refractories have high melting points, they have to be specified very carefully against the mineral matter in the solid fuel. Alkali metals (especially potassium and sodium) can form new refractory compositions with different properties including phase changes that spall the refractory thus losing the protection. The mineral matter in biomass can also react to form low melting point eutectics that form fluxes and bond the mineral matter together in a slag or clinker that causes mechanical problems in combustion systems.

Time is the second component of successful combustion, because sufficient time is needed for reactions to go to completion. The time required is a complex relationship with the partial pressure of oxygen and temperature. When both are high, the reaction time is short. At lower temperature conditions, the reactions may well not go to completion, with for example the oxidation of organic compounds resulting in products of incomplete combustion (PIC) which include reactive organic molecules and carbon monoxide, as well as unburnt carbon which is a particulate often called soot.

Turbulence or mixing is essential if individual volumes inside of the combustion zone are not to locally consume the available oxygen (i.e., $\lambda < 1.0$), and result in PIC formation. Turbulence is also an aid to heat

transfer after improving the convective heat transfer from the combustion chamber to the cooking vessel or boiler ensuring that the average temperature is as high as possible.

A separate concept related to turbulence is also important, and that is draft. Blowing on the embers of the fire will rapidly increase the temperature from black to bright red and accelerate the combustion. In the industrial scale boilers, there is forced draft with quite high air velocities meeting the solid fuel and combustible gases in the range of 5–10 m s⁻¹. In domestic heating appliances a critical component is the chimney – an insulated tube after the firebox. Here the low density of the hot post combustion flue gases (typically half to one third that of the ambient air) causes the external atmospheric air to enter the firebox and propel the flue gases up the chimney until they are dispersed in the atmosphere. Long chimneys and very high temperatures can create a very high pressure differential and thus a high air flow – controlling the area of the air inlet to the firebox can create high linear velocities or a high draft to enhance the temperature. Kilns to produce lime from limestone (CaCO₃) and even iron bloom production has been carried out in dry wood-fired shaft furnaces [25]. The key to high temperatures whether in a kiln or a firebox is to have a high rate of heat release relative to the rate of heat loss through the walls by conduction and radiation, and in the flue gas.

Once the chemical energy of the solid fuel has been released through combustion, the next challenge is to efficiently transfer that heat to the cooking vessel, boiler, or process.

Heat transfer has several modes, namely, radiative, conductive, and convective transfer. A very high temperature source above 1,000°C can radiatively transfer a large amount of heat per unit area of a surface to its surroundings. Heat can also be conducted through the walls of the combustion system to the required application. Finally the heat can be transferred convectively from the combustion gases to the recipient. As an example in an industrial boiler, the water cooled walls remove radiative heat from the combustion volume, and the first bank of boiler tubes are heated both by radiation and by convective heat transfer, while the downstream tubes receive convection heat. Convective heat transfer depends on the velocity of the gas flow, the

exposed surface area, and whether or not the flow is turbulent or laminar.

The Rocket stove [26] is an example of an innovation that responds to the physical and chemical requirements for good combustion and heat transfer at a small scale in an interesting and relatively low tech way. The design starts with a single opening for both fuel and the air for combustion – thus allowing the control of λ , while the number of sticks (i.e., the rate of fuel) addition to the combustion chamber controls the rate of heat release in a relatively small volume. The combustion chamber is a small insulated volume at the base of an insulated chimney. The chimney provides the draft to draw in the combustion air, and the fuel burn out is completed as the primary combustion products traverse its length. Heat transfer is obtained at the end of the chimney and requires a good fit between the pot and the chimney termination – sometimes aided by a pot skirt (an annulus that channels the flue gases up and along the sides of the pot) to ensure that the hot flue gases transfer their heat by convective heat transfer. Such stoves have a much-improved efficiency and also burn out much more of the PIC resulting in lowered carbon monoxide and particulate emissions.

Biomass Cookstoves

The most frequent form of biomass combustion is in a simple hearth. The fuel, wood, straw, or other material placed on the ground is ignited and then fuel is added to the fire, while some sort of support for a cooking vessel is arranged over the fire to receive the heat to boil water, or provide a surface for cooking breads, or grilling meats and fish. Prehistoric hearths provide evidence of cooking and social life to archeologists, and the carbon remaining in the hearth is often used to carbon date the site as far back as 750,000 years [27].

The hearth can be against a back wall, or free standing with what is a common arrangement of three stones in a triangle, with two of the three stones set in the ground for stability, and the third moveable to accommodate different sizes of cooking vessel. Three-stone stoves are easily assembled, easy to regulate, burn a wide variety of fuels, shapes and sizes, and also provide light, heat, and social focus [6] today as they did in

prehistoric times. The power output is controlled by the addition or withdrawal of fuel. If the fuel is wood, then sticks or branches are fed from the edges toward the center where the flame is. While the flames move out from the center to the edges along the sticks, their radial spread is limited as the burning zones get separated and no longer have coupled heat transfer by radiation, and effectively are extinguished. In order to maintain constant power output, fuel has to be constantly moved toward the center of the fire. Since the flame is in the open, windy conditions will cause fluctuations in the output by literally blowing the heat out from under the cooking pot. The low cost of the three-stone stove is because it uses widely available materials, and the efficiency under controlled conditions can be surprisingly high. However, the emissions as smoke and PIC are also very high. In engineering terms, the fuel on the ground with fire in a radius of 5–20 cm is a very small-scale approximation of what is called a pool fire. Since the fuel is confined to a stationary surface, the air supply for combustion has to sweep over the top of the fire and can only be drawn in through the buoyancy of the hot combustion gases. The convective force and the large external area for the fresh air access combine to provide a very small draft velocity. So, temperatures are low, and like in a diffusion flame there are fuel rich (i.e., high in PIC) zones separated from the mixed combustion zones. In nearly all ICS, the fire is supported on a grate with the idea that primary air flows through the fuel bed with λ below 1. Then above the fuel bed, secondary air (sometimes preheated) is added to complete the combustion with λ above 1 to get around the issues of the pool style buoyant combustion of the three-stone fire.

Efficiency of cookstoves is a surprisingly difficult thing to measure and or define. The topic will be returned to later. However, here it is supposed that it is measured by the heat delivered to the pot relative to the heat input to the stove. For example, three-stone efficiencies are described of up to 20–30+% under laboratory conditions in which the rate of fuel supply is controlled and the pot distance to the fire is varied for maximum heat transfer [1, 28].

One of the most widely accepted measurements of stove efficiency, the Water Boiling Test (WBT) originated with VITA [29]. Basically, the test

methods simulate the high power phase needed to bring a food to a boil, followed by a low power (i.e., to simmer) process of cooking while using water to simulate food.

Stove performance is measured by its Percent Heat Utilized (PHU). Alternatively, the Specific Consumption (SC) can be specified. The Percent Heat Utilized of a stove is the percentage of heat released by the fire that is absorbed by the water in the pot. The Specific Consumption is the total quantity of wood used for the simulated cooking process divided by the amount of water “cooked.” Results from tests for different stoves can be used to rank the stoves, and more usefully the development of a standardized test was important as researchers tried to understand the effect of different design parameters. Nevertheless, boiling water in a controlled laboratory setting is not likely to reflect the real world situation of cooking different foodstuffs in a home or institutional setting. The current accepted version of the boiling water tests is obtainable from ehs.sph.berkeley.edu/hem/hem/.../WBT_Version_3.0_Jan2007a.pdf. The experience of stove performance in the field can be correlated with the laboratory test. Other more realistic tests have been devised by many research groups under names such as CCT (Controlled Cooking Test) or the KPT (Kitchen Performance Test).

Table 2 summarizes the results not just of the Water Boiling Test (WBT) (3.0) but also of the WBT (4.0), which includes emissions testing of stoves (for WBT (4.0) see <http://www.pciaonline.org/testing/wbtcomment>).

In a series of tests of stoves without chimneys in five broad classes, the following results were obtained (Table 2).

The detailed results behind Table 2 are the median value and a range. Though, it should be noted that the number of stoves tested in each class is varied, and that outliers have been neglected. Tests on a smaller group of stoves show very similar performance thus showing the value of the WBT as a universal test tool in the design and evaluation of stoves [30]. The value for energy use in charcoal fired stoves is not that which was measured during the WBT, since charcoal is a biofuel with significant energy losses in its production. The measured WBT value of 20 MJ has been multiplied by 2.5 to reflect the energy lost during artisanal charcoal production.

Biomass Energy Heat Provision for Cooking and Heating in Developing Countries. Table 2 Summary of efficiency and emissions performance of several classes of wood-stove data derived from [15]

Stove type	MJ in WBT	CO (g)	PM (g)
Three stone	22+/-8	70+/-25	1.6+/-0.8
Simple ICS	15+/-5	50+/-10	2.5+/-2
Rocket	13+/-3	18+/-3	1.0+/-0.6
Gasifier	20+/-5	22+/-6	0.5+/-0.25
Forced air	10+/-1	5+/-2	0.1+/-0.05
Liquid/gas	8+/-2	5+/-2	< 10 mg
Charcoal	50-60*	100+/-20	0.25

*Correcting for the efficiency of charcoal production from fuelwood

What is clear from the results is that fan-assisted forced air circulation stoves using small wood pieces can achieve nearly the same performance in all three categories as a propane stove. The requirement for fuel preparation to small dry pieces may be a constraint in many circumstances. Typically, the size of the fuel particle should be below 10% of the combustion zone diameter and with the high draft of the forced air circulation stove the combustion zone is quite small with a very high rate of heat release.

Another feature of note is the scatter of performance in the simple stoves. It is known that dimensions for the combustion chamber and the fit with the pot are actually quite critical and that varying manufacturing tolerances can result in stoves that are marginally more efficient, but with very little improvement in the emissions profile over the three-stone stove.

Health Effects of Biomass Cookstoves

The impact of using wood-fired cookstoves indoors has been known for a long time with a strong and direct link to diseases such as COPD (Chronic obstructive pulmonary disease) and weaker links to low birth weights of children and premature cataracts in adults

exposed to open fires such as women and children. The topic did not start to rise to the top of the research agenda until a major analysis was published [31]. This was more fully quantified by the World Health Organization in a paper [32] which ranked indoor air pollution as 8th in the list of disease risk factors being responsible for 2.7% of the global burden of disease. The overall burden due to indoor air pollution from stoves measured in Disability-Adjusted Life Years or DALYs, (a measure combining years of life lost due to disability and death) is five times greater than that of outdoor air pollution. The statistics for high-mortality developing countries show that indoor air pollution is responsible for 3.7% of the overall disease burden.

A major call to action by the WHO [11] outlines in detail what the issues and their impacts have on the United Nations' Millennium Development Goals (MDG). There are no energy topics in the MDG, despite the lack of clean energy availability being the ultimate cause of many problems that are being identified as MGD. The proximate MDG goals affected are: #4 child mortality reduction; #3 gender equality and empowerment of women; #1 opportunities for income generation and extreme poverty eradication; as well as #7 on ensuring environmental sustainability.

The international community has rallied around this cause in the last decade. The Shell Foundation (www.shellfoundation.org) has a major program "Breathing Space" which takes the view that the indoor air pollution challenge has to be solved through market-thinking and private sector involvement. This is a break with former programs in which NGOs and governments have given away or subsidized ICS. There is a partnership with Envirofit International, a US not-for-profit organization to design and market a new range of improved stoves – and to find commercial partners to manufacture and distribute stoves. Their aim is to see 10 million stoves sold in five countries in the next 5 years.

The umbrella organization addressing the cookstove challenge is the Partnership for Clean Indoor Air (PCIA; www.pciaonline.org). Established in 2002 after the Johannesburg World Summit on Sustainable Development, the PCIA has garnered over 400 public and private organizations who contribute resources and expertise to address four critical areas: (1) meeting social and behavioral needs; (2) developing

local markets; (3) improving technology design and performance; and (4) monitoring impacts and interventions.

Climate Change and Woodstoves

At first glance, the cookstove impact on global warming is the extent of the emissions of PIC. Many of which have a Global Warming Potential (GWP) many times that of carbon dioxide. However, that would be making the assumption that the entire emission of carbon dioxide from wood combustion in cookstoves was renewable. That is to say the biomass is regrown after harvesting, and without any direct land use change (dLUC) or indirect land use change (iLUC). The evidence presented earlier as well as many field observations show that some proportion of the wood extracted is in fact nonrenewable. In the extreme case of high demand and adverse climate changes almost all of the biomass fuels are nonrenewable as was the case in the Sahel in the 1970 and 1980 decades when population growth and the decadal shift of the tropical inter-convergence zone [33] created famine due to a drought in the Sahel [34]. Food and energy poverty were extreme across the entire southern boundary of the Sahara.

The situation in Africa was the reason for the heightened interest in biomass-fueled cookstoves in that period. Today it is clear that there is some degree of deforestation, and of land degradation in all areas with large scale use of biomass for heating and cooking, due for example to increased soil erosion. The extent of this nonrenewable biomass use is not known with certainty, and has to be estimated. The problem may in fact have a high degree of granularity with communities suffering shortages within a region that has overall a surplus of woodfuels [35]. For India, it is estimated that only 10% of the biomass used is nonrenewable [36].

The emission of PIC is in inverse relationship to the combustion efficiency of the appliance. A linear correlation has been shown with an $R^2 = 0.79$ in different appliances and using different biomass fuels from fuelwood to straw [37]. Also the ratio of carbon monoxide to carbon dioxide produced has been investigated to be a good proxy for the measurement of efficiency, which as described above is not very easy to accomplish.

The PIC themselves range from atmospherically short-lived complex organic molecules (often described

as non-methane hydrocarbons NMHC, or non-methane volatile organic carbon NMVOC), and carbon monoxide with small GWP to long-lived actors with high GWP, substances such as methane.

There are two other biomass combustion sources of GWP, nitrogen oxides (NO_x) and particulates. The major concern on nitrogen oxides is with N_2O dinitrogen oxide which has a GWP of 386 times that of CO_2 . However, it is difficult to correlate NO_x emission from small combustors, as there are contributions from the biomass fuel (Fuel bound nitrogen) and from the temperature and time of combustion oxidizing part of the nitrogen from the air. The temperature and time are related to the actual stove design and its operation with respect to lambda.

Smoke (i.e., particulate emissions) is a major part of the health impact of non-ventilated stoves as well as having significant GWP. The size range of the particulate is very relevant. Large particles above $10\text{ }\mu\text{m}$ do not enter the respiratory system, and are relatively short lived in the atmosphere. Smaller particles ($\text{PM}_{2.5}$; i.e., $< 2.5\text{ }\mu\text{m}$ in diameter) can enter the pulmonary system, and are long lived as aerosols in the atmosphere (days to weeks). The atmospheric effects of the carbon in the smoke are still being debated. All biomass combustion with smoke (whether a forest or grass fire, or an open stove with low efficiency) generate organic compounds and black carbon. These agglomerates enter into the atmosphere and become aerosols. Black carbon aerosol absorbs light and contributes to warming, while the organic (white) aerosol reflects and cools the atmosphere. Eventual deposition of black carbon on glaciers will result in increased absorption of solar energy and increase mass loss. A review of black carbon emissions [38] suggests that residential use, primarily in cookstoves burning coal and biomass, is the major source of black carbon and that the region itself is the major contributor of black carbon to the atmosphere. The South Asian atmospheric brown cloud (ABC) covers from the Arabian sea to the Southeast Asian region for the majority of the northern hemisphere winter, and is composed of a large number of aerosols including inorganic dust. However, a major proportion is derived from biomass. The short lifetime of the black carbon in the atmosphere means that it has a short term 20 year-GWP of about 2,200 kg carbon dioxide equivalent while the 100 year-GWP is 500–680 (Table 2 in [38]).

The estimated $30\text{--}40\text{ EJ y}^{-1}$ of primary energy in biomass fuel use in cookstoves assuming there are no ICS, and that 10% of the carbon used is nonrenewable will have gross emissions of about $2.4\text{--}3.5\text{ Gt CO}_2$ equivalent, if the cookstove was the three-stone. This is computed based on an overall efficiency from wood input to energy delivered in the pot of 10%. According to [39], the greenhouse gas emissions are about 800 kg GJ^{-1} delivered, comprising about half black carbon, one quarter methane, 20% carbon monoxide, and some N_2O . This result is of course very sensitive to the assumptions, the stove performance envelope for efficiency and greenhouse gas emission components.

From Table 2, the general range of ICS efficiency is 1.5 times better than the three-stone while the CO and PM values are only somewhat different. The original data shows that many ICS provide efficiency gains, without a significant improvement in the emissions. Thus the bottom range of ICS stoves would lead to less primary energy consumption, but nearly all of the emission components would remain about the same, leading to a range of $1.3\text{--}1.6\text{ Gt CO}_2$ equivalent. Moving to the rocket stove (at a similar efficiency to the ICS) with its known threefold reduction in CO and its almost halving of PM would change the equation to greenhouse gas emissions of about 350 kg GJ^{-1} delivered, further reducing the emissions to around $0.70\text{--}1.0\text{ Gt CO}_2$ equivalent.

The LPG case with its greater efficiency and ignoring the carbon dioxide equivalent costs of the fuel distribution system needed to replace woodstoves would have an impact of CO_2 equivalent of 181 kg GJ^{-1} of delivered energy – for a total impact in replacing biomass primary energy of about 0.4 Gt CO_2 equivalent. The forced air biomass stove would also achieve LPG like performance on efficiency, methane, and carbon monoxide, though the particulate would still be about 10 times larger than the LPG stove, but one tenth that of the simple ICS.

Table 3 summarizes the assumptions above to arrive at the estimated greenhouse gas emissions of the biomass-fueled cookstove use. Without an accurate basis for estimating the effect of nonrenewable and unsustainable biomass removals, the following assumptions have been made. The delivered energy to the global cook pot is assumed to be 3 EJ y^{-1} . If the entire stove population was the three-stone fire at 10%

Biomass Energy Heat Provision for Cooking and Heating in Developing Countries. Table 3 Estimation of the total emissions of CO₂ equivalent for four different stove scenarios

Stove	Basis	Primary energy	Fraction NR	NR-CO ₂	kg CO ₂ -equivalent per GJ delivered				Total emissions Gt CO ₂ equivalent	
	Efficiency	EJ		Gt	CH ₄	N ₂ O	CO	BC	Emissions	Including NR C
3-stone	0.1	30.0	0.30	0.89	189.1	35.5	166	430	2.46	3.35
ICS	0.15	20.0	0.20	0.39	89.8	28.4	70.9	106	0.89	1.28
Fan-assist	0.5	6.0	0.05	0.03	90	0	8	20	0.35	0.38
LPG	0.55	5.5	1.00	0.36	0	10	0	0	0.03	0.39

NR nonrenewable biomass resource, BC black carbon, NR C nonrenewable carbon

efficiency (probably a low estimate) then the 30 EJ of input required would be unsustainable, with 30% of the biomass being nonrenewable. Increasing the efficiency to 15% for the lower end of the ICS population would require only 20 EJ of input and an estimated nonrenewable contribution of 20%. At the efficiency of the fan-assisted stoves only 5% is proposed as nonrenewable due more to local situations of fuel wood deficit rather than regionally.

Findings and Discussion

The domestic biomass cookstove as it exists today is responsible for a wide range of diseases and illnesses that rank it 8th in the list of human health hazards, and for humanitarian reasons this has to be mitigated. The economic cost of the biomass cookstove is also very large both to those directly affected, and through the impacts on the climate system. However, the local effect is hidden when the economy is not monetized. Illness, low productivity, and the time spent in wood and biomass collection by women and children are all components of this cost to the individual and society. And while climate change mitigation is also important, the likely level of greenhouse gas (GHG) is somewhere between 1.3 and 3 Gt of CO₂ equivalent, and this is less than 10% of the most recent global estimate of the total direct fossil fuel emissions of carbon dioxide at 30.8 Gt in 2009 [40]. Like the challenge of reducing the GHG impact of automobile use – the solutions involve the purchasing and use decisions of billions of people and are thus unlikely to be effective without major technological changes in the stove technology. There

are advantages in combining society's response to both the health and climate challenges along with meeting the Millennium Development Goals [41].

The thought experiment of replacing all biomass-fired appliances with LPG, if carried out would remove the health impacts, and surprisingly it would also reduce the climate change impact as measured by total GWP of cookstoves by a factor of 4–5 despite the fossil carbon content of LPG. At the same time, the use of LPG would remove pressures on the natural environment due to wood harvesting.

This utopian solution is far away, and may never be realized. Even today, when the UN High Commission for Refugees has to meet humanitarian crises the energy source that is most often used is the biomass and wood resource available locally. The logistics and the direct costs make this the solution of choice for field kitchens and for family use in camps for internally displaced persons or refugees.

With a world population that is gradually urbanizing the number of people without access to modern energy should decrease, as it is much easier to serve the high population densities of cities and the peri-urban areas with electricity and gas. Nevertheless, the rural energy challenge will remain and will require ICS and wherever possible more efficient fuels.

However, as is well known, ICS diffusion has continued to meet many obstacles since the World Bank surveyed this question in 1994 [42]. Even an assessment from 1995 has its echoes today in the many programs that have tried and failed to gain the traction needed for wide scale dissemination [43]. More recent sources (e.g., [44]) emphasize that in less-developed countries

and especially in sub-Saharan Africa the majority, that is, 90% and 83% respectively lack access to modern fuels. Worse still given the initial concerns about the Sahel discussed in the introduction only 6% of those using traditional biomass in these regions have access to ICS.

The 60+ years of attempts to diffuse improved stoves and the extensive technical research of the last 2 decades have arrived at a single conclusion.

Simply put there is no easy low cost technological fix for unvented natural draft biomass-fueled cookstoves.

The theoretical and detailed practical background description above shows that at small scales of average thermal output around 2 kW for solid fuel combustion under natural draft conditions, the efficiencies are poor and emissions are higher than those recommended for 8 h exposures by the World Health Organization (WHO). Miniaturizing forced draft combustion with small particle size fuels can come close to LPG in efficiency and emissions but the fan, its electricity supply and maintenance as well as first cost means that for most of the population needing it, the infrastructure is probably just not there to support the technology. Even the diffusion of LPG stoves in the development context is challenging, and this is for a well defined product, with a very high acceptance by the middle class in urban areas in developing countries [45].

Technology is extremely hard to describe and to define but is clear that ICS technology is much more than just the stove or heating appliance and incorporates many other technologies in the background. The evolution of technology itself relies on technology in associated areas to be successful as outlined by [46]. The Stanford Program on Energy and Sustainable Development has attempted to address the question of stove technology adoption and reasonably enough arrives at three major topics: motivation to acquire new technology; affordability; and the magnitude of the change in lifestyle and attitudes required [47]. Despite going into each of these areas and producing rational explanations, the Stanford study, and many prior studies omit to make the key observation about the potential community of users of ICS – many of the users are in countries that are failing and are members of the “Bottom Billion” identified by Paul Collier [48]. Curiously, Collier did not actually identify the countries other than they are mostly in Africa and Asia, but

what he did identify are the issues that make them fail, the traps of: conflict; natural resources; and being landlocked. Hard-nosed solutions are also proposed that impact on the food and energy poverty issues; their intention is to put the countries on a growth pathway not an aid dependent pathway.

The history of the last 4 decades demonstrates that where stove programs work best is in growth economies such as India and China. The challenge is to translate this to the Bottom Billion who are more likely to be totally dependent on biomass. And the challenge is in many more areas of technology than just energy. The final observation is a quote from a Microsoft pioneer, Kent Toyama who went into the promotion of information technologies in development [49]. His findings clearly cover much more than ICT (information and communication technologies).

“The challenge of international development is that, whatever the potential of poor communities, well-intentioned capability is in scarce supply and technology cannot make up for its deficiency.”

“This point may sound reasonable enough when stated in the abstract, but it has an important consequence for anyone expecting to save the world with technology: you can’t. . . at least, not unless the technology is applied where human intent and capacity are already present, or unless you are willing also to invest heavily in developing human capability and institutions. . .”

Future Directions

Clearly all efforts to improve the kitchen conditions for the large population of women and children exposed to smoke have to be encouraged. The actions of the two major public-private initiatives in this area have to be supported.

Improved statistics on income poverty, food and energy poverty, and the use of GIS to pinpoint and intervene in areas of high environmental stress is needed through the enhancement and maintenance of integrated assessment systems such as WISDOM.

The rapid diffusion of alternatives to natural draft biomass stoves is essential whether it is of forced air biomass stoves or LPG burners. Both will reduce the exposure to pollutants both indoor and to the

atmosphere with respect to PIC and greenhouse gas (GHG) emissions. The natural resource implications are of course minimized while the GHG impact is also reduced significantly. While research to improve user safety and to optimize these systems is needed, even more research is needed in the entire logistics chain. Since experience to date shows that irrespective of cost to the user, and indeed some stove interventions have been highly subsidized, the net envelope of technologies involved require high investments in education and institutions to develop receptor capacity and ensure uptake of the clean burning technology.

The post second world war deployment of ICS has still not developed a universal and successful model for market deployment, nevertheless the current efforts have to be expanded while current and past programs have to be rigorously evaluated for lessons learned. However, it is also evident that natural draft ICS without chimneys have variable performance between different models, especially with respect to PIC and particulate emissions. An internationally recognized performance and certification process is needed if the use of ICS is in fact going to address the health-related problems of using biomass.

For the poorest billion or so users the cookstove problem is just one facet of a much larger problem of poverty and is associated with food and energy poverty and the need for implementation of the Millennium Development Goals to address these.

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Biomass Energy Heat Provision in Modern Large-Scale Systems

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Article Outline

Definition of the Subject

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Characteristics of Biofuels and Combustion Principles

Industrial Combustion Technologies

Summary

Combustion-Based Power Generation Processes

Emissions from Combustion and Ash-Related

Problems

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Definition of the Subject

Combustion of solid biomass is the oldest and most mature technology for the production of heat and the main source for the provision of renewable heat today. The applications of biomass combustion comprise a wide range from domestic combustion units with installed capacities of a couple of kW to district heating plants in the MW range and industrial combined heat and power units up to a nominal boiler capacity of 590 MW_{th} [1].

Biomass is the most important renewable energy source in the European Union. In the field of energetic utilization of solid biomass, combustion is the most advanced and market-proven application. Consequently, the energetic use of solid biomass is primarily based on biomass combustion at present. Biomass combustion technologies cover fixed-bed, fluidized bed, and pulverized fuel combustion systems. They are currently available for different types of biofuels covering a wide range of plant capacities. Concerning plant size, the different applications of biomass combustion can be divided into small-scale biomass combustion systems (capacity range below 100 kW_{th}), medium-scale combustion systems (capacity range between 100 kW_{th} and 20 MW_{th}), large-scale combustion systems (capacity range above 20 MW_{th}), and co-firing of biomass in coal-fired power stations (capacity range usually some 100 MW_{th}).

Emission of pollutants from biomass combustion is due to either incomplete combustion or the release and conversion of fuel-bound elements. Incomplete combustion can lead to high emissions of not fully oxidized pollutants such as CO, C_xH_y, soot, and PAH. Relevant improvements to reduce these emissions have been achieved by optimized furnace design and process control; but there are still further improvements possible in many cases. The release and conversion of pollutants such as NO_x, SO_x, HCl and particles are formed as a result of fuel constituents (e.g., N, K, Na, Pb, Zn, Cl, S). Primary measures such as air staging and fuel staging offer a certain potential for NO_x reduction, which is increasingly used nowadays. Regarding particle emissions, so far only secondary measures (like particle precipitation units) are effective but only economically viable for medium and large-scale units. Further efforts and developments are needed for emission reduction and

for plant optimization as well as for the development of combustion technologies for non-wood fuels. In this respect especially energy crops and agricultural as well as industrial biomass residues are of relevance.

This chapter describes the present state of technology and current developments regarding modern medium and large-scale biomass combustion systems.

Introduction

Combustion is the most widely applied technology for heat and power production from solid biofuels at present. Several technologies exist, which are available in the size range from domestic heating of a couple of kW thermal capacity up to industrial combined heat and power production of several hundred MW thermal capacity. The traditional biomass combustion technologies are designed and operated to produce heat. However, the importance of combined heat and power production is increasing [2]. Power production is commercially performed by steam turbines and steam engines in large-scale combustion plants and by organic Rankine cycles for medium-scale applications, while technologies such as Stirling engines and micro-turbines are options for the use in the small scale (below 100 kW_{el}).

The current European utilization of biomass combustion is mainly applied to the following processes:

- Heat generation in small-scale domestic applications for space heating and cooking
- High-temperature heat production in medium- and large-scale applications for district and process heat supply (e.g., district heating networks, wood processing industries, drying purposes)
- Steam production for driving steam turbines as well as for combined heat and power (CHP) applications in large-scale units
- High-temperature heat production for power or combined heat and power supply using heat carriers (e.g., thermal oil, air) in medium and large-scale units.

In recent years, the thermal utilization of solid biomass for heat and electricity production has gained importance. Within the European Union (EU) in particular, biomass is the most relevant renewable energy source and thus contributes substantially to the CO₂ emission reduction targets defined within the Kyoto protocol.

Within the EU, several political measures have been initiated with the aim of supporting the utilization of renewable energies including the Res-e Directive (2001), the EU Biomass Action Plan (2005), Energy and Climate Change Package (March 2007), and the Renewable Energy Directive (June 2009). Within the scope of these measures the following targets have been defined:

- 20% renewables by 2020
- 20% reduction of greenhouse gas emissions by 2020
- 20% increase of energy efficiency by 2020
- 10% increase in biofuels by 2020

Figure 1 shows the estimated primary energy consumption and total turnover of biomass combustion plants in the EU for 2008 as well as the outlook for 2020. The calculations are based on the present market [3–7] and the assumption that the EU 2020 targets will be achieved [8]. The results show that an average market growth rate of approx. 8.3% p.a. is expected. The overall market volume will grow up to 260% and the primary energy consumption from biomass will more than doubled until 2020.

Biomass energy is used for different purposes in various countries. While the markets in Sweden, Denmark, and Finland are directed toward large-scale

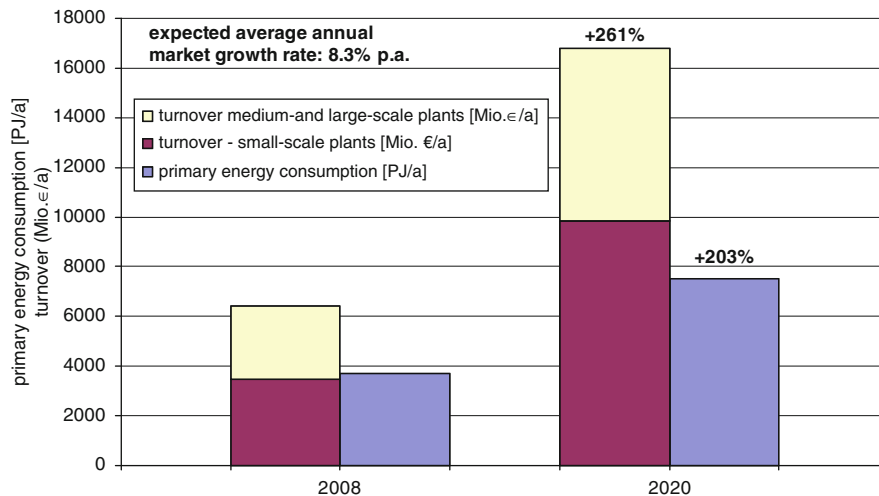
applications (above 20 MW_{th}), the focus elsewhere in Europe is on small (below 100 kW_{th}) and medium-scale (0.1 till 20 MW_{th}) systems.

This chapter explains relevant characteristics of biomass fuels and combustion principles, summarizes the most common concepts of combustion technology for solid biomass fuels used in medium and large-scale combustion today, and gives a short overview about possible combustion-based technologies for power production. In addition, emissions from combustion of solid biomass fuels and ash-related problems are discussed and research and development trends are presented. Co-combustion of solid biomass with waste or coal is not covered in this report [9, 10].

Characteristics of Biofuels and Combustion Principles

Characteristics of Biofuels

The chemical composition of biofuels can vary concerning both, the concentrations of the main elements (C, H, O, N) as well as the ash content respectively the concentrations of ash-forming elements. The ash content can be seen as a guiding parameter indicating increased ash-related problems with raising ash content. However,



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 1

Estimated primary energy consumption and total turnover of biomass combustion plants in the EU for 2008 and outlook for 2020 (Explanations: small, medium, and large-scale plants considered; small-scale plants: nominal boiler capacity below 100 kW_{th}; calculations based on present market and achievement of EU 2020 targets [3–8])

detailed information about the single ash-forming elements is needed in order to evaluate a biofuel with respect to different ash-related problems that can occur. Thereby also interactions between these elements have to be considered. Below some specific characteristic parameters of biofuels, which can be taken as a basis for the evaluation of a fuel are summarized.

Table 1 shows important physical properties of solid biofuels and their effects on the combustion process and the plant design. The moisture content of the fuel provides information concerning the general applicability of a certain fuel in a combustion process and its storability.

Biomass Energy Heat Provision in Modern Large-Scale Systems. Table 1 Combustion-relevant characteristics of solid biomass fuels – physical properties

Properties	Effects
Moisture content	Storability, dry matter losses, NCV, self-ignition, plant design
NCV, GCV	Fuel utilization, plant design
Volatiles	Thermal decomposition behavior
Ash content	Dust emissions, ash manipulation, ash utilization/disposal, combustion technology
Ash melting behavior	Operational safety, combustion technology, process control system, hard deposit formation
Fungi	Health risks
Bulk density	Fuel logistics (storage, transport, handling)
Particle density	Thermal conductance, thermal decomposition
Physical dimension, form, size distribution	Hoisting and conveying, combustion technology, bridging, operational safety, drying, formation of dust
Amount of fines	Fuel feeding, particle entrainment
Abrasion resistance (wood pressings)	Quality changes, segregation, fine parts

The ash content has to be considered concerning the de-ashing system, ash storage, ash utilization, the grate design as well as the fact that a high ash content lead to higher entrainment of ash particles from the fuel bed with the flue gas and consequently to increased deposit formation, erosion, and particulate matter emissions. Therefore, it is an important parameter to be considered during plant design.

The ash melting behavior of ash mixtures is characterized by the content and by the melting temperatures of the single ash-forming elements respectively their compounds. Si, Ca, and Mg increase and K, Na, and P as well as Cl decrease the ash melting temperature. The ash melting behavior affects the combustion technology and the process control system and is an important factor concerning deposit formation and operational safety.

The bulk density of the fuel has also to be considered concerning fuel transport, storage, and feeding systems.

The amount of fines is relevant concerning the appropriate selection of the combustion technology and the process control. Regarding small-scale systems, the amount of fines is also of big relevance concerning the fuel feeding system (e.g., this is a quality parameter for pellets). In medium and large-scale plants the amount of fines is an important factor regarding particle entrainment (i.e., they can cause strain formation and incomplete burnout).

Table 2 shows combustion-relevant chemical properties of solid biofuels. For a complete characterization of biomass fuel content of C, H, O, and N as well as the gross calorific value (GCV) should be determined since they provide basic information concerning the general applicability of a certain fuel in a combustion process and regarding the energy content of a fuel. The N content is of special relevance concerning NO_x emissions. Moreover, ash-forming elements have to be divided into nonvolatile elements such as Si, Ca, Mg, Al and Fe, semi-volatile elements such as P and Mn, and rather volatile elements such as K and Na. During combustion semi-volatile and especially volatile elements are partly released from the fuel to the flue gas and react with other elements such as S, Cl, or CO₂ in the flue gas. Major ash-forming elements originate either from the biomass (plant) itself or from

Biomass Energy Heat Provision in Modern Large-Scale Systems. Table 2 Combustion-relevant characteristics of solid biomass fuels – chemical properties

Properties	Effects
Carbon (C)	GCV (gross calorific value)
Hydrogen (H)	GCV (gross calorific value), NCV (net calorific value)
Oxygen (O)	GCV (gross calorific value)
Chlorine (Cl)	HCl-, PCDD/F emissions, corrosion, lowering of ash melting temperature
Nitrogen (N)	NO _x -, N ₂ O-emissions
Sulfur (S)	SO _x - emissions, corrosion
Fluor (F)	HF emissions, corrosion
Potassium (K)	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols, ash utilization (plant nutrients)
Sodium (Na)	Corrosion (heat exchangers, superheaters), lowering ash melting temperature, formation of aerosols
Magnesium (Mg)	Increase of ash melting temperature, ash utilization (plant nutrients)
Calcium (Ca)	Increase of ash melting temperature, ash utilization (plant nutrients)
Phosphor (P)	Ash utilization (plant nutrient), ash melting, aerosol formation
Heavy metals	Emissions, ash utilization, formation of aerosols

impurities such as soil, stones, and residues from the preprocessing of the fuels. Elements such as P, K, and Na, for example, are part of the cell matrix of plants and elements such as Ca and Si are embedded in the plant fibers. In wood fuels usually Ca is the dominating major ash-forming element while in herbaceous biofuels significantly higher Si contents prevail.

Subsequently, the resulting sulfate, chloride, and also carbonate compounds may form fine particles by nucleation (formation of aerosols) or condense on already formed aerosols and coarse fly ash particles as well as on heat exchanger surfaces (ash deposit formation). In most fuels mainly K and Na are involved in these processes. In P-rich fuels also a part of the

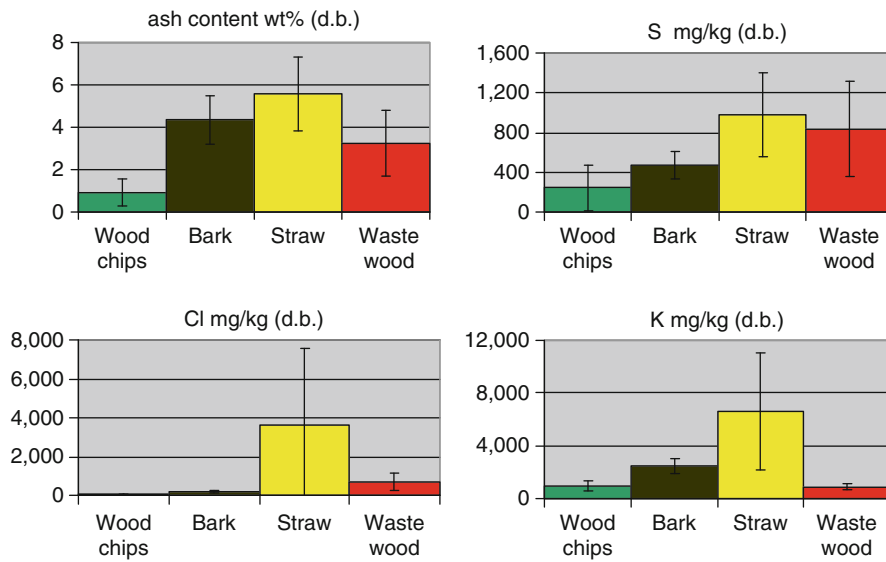
organically bound P is released to the flue gas and is involved in aerosol and deposit formation mainly via the formation of KPO₃, P₂O₅, and P₄O₁₀ [11].

Minor ash-forming elements (i.e., Zn, Pb, Cd, Cu, Cr, Co, Ni, Mo, As, Sb, Hg, Tl) are mainly of interest concerning problems with too high gaseous and particle-bound heavy metal emissions as well as regarding the ash utilization. Moreover, the presence of heavy metal chlorides in ash deposits can significantly reduce the melting temperatures of the deposits thus leading to increased deposit formation and corrosion rates.

S and Cl are relevant elements concerning gaseous emissions (SO_x, HCl), fine particle (aerosol) formation, as well as ash deposit formation on boiler tube surfaces. Ash deposits are mainly formed by alkali metal salts such as K₂SO₄ and KCl. High Cl-contents of the fuel therefore also increase corrosion-related problems especially due to ash deposits with high Cl-contents. Moreover, Cl reduces the ash melting temperature of deposits. Due to these deposit formation and corrosion-related issues impact of the S- and Cl-contents of the fuel on the superheater surface temperatures (steam temperatures) in steam boilers is given. Furthermore, it has to be taken into account that increasing S and Cl concentrations in the flue gas result in a change of the dew point of the flue gas, which has to be considered concerning possible condensation in the heat exchangers and the flue gas cleaning systems.

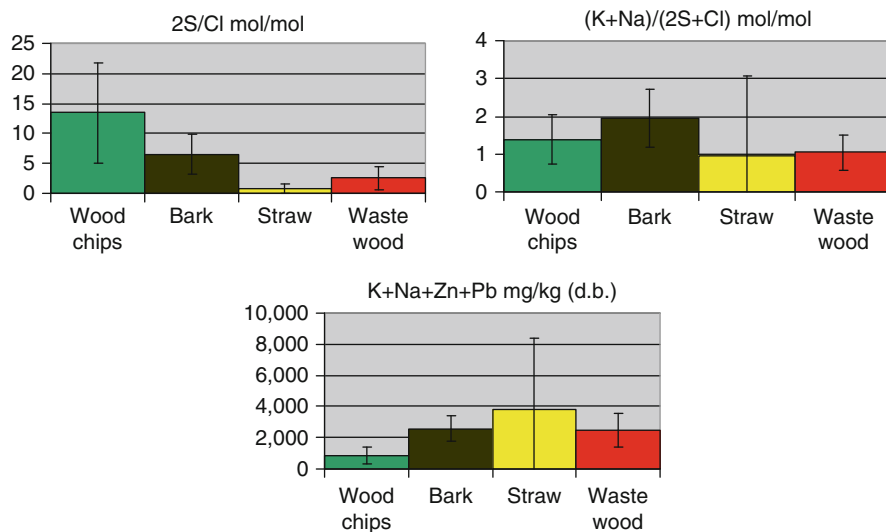
Figure 2 exemplarily shows how the chemical composition and the ash content of different solid biomass fuels can vary. The ash contents for bark and waste wood are high and even higher for straw while the ash content of pure wood fuels is comparably low. The sulfur content is high in straw and waste wood. The lowest sulfur contents are found in wood chips. The chlorine and potassium content of herbaceous fuels is considerably higher than of woody fuels, which directly affect aerosol formation and ash melting. The big deviation between different biomass fuels concerning their contents of ash-forming elements clearly underlines the relevance of considering the fuel-specific properties during plant design.

Figure 3 shows relevant guiding parameters which can be derived from the chemical compositions of different solid biofuels. An important guiding



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 2

Chemical compositions of different solid biomass fuels – ash, S, Cl, K



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 3

Chemical compositions of different solid biomass fuels – relevant guiding parameters

parameter is the molar ratio $(K + Na)/(2S + Cl)$. During combustion S and Cl preferably form alkaline (K and Na) sulfates and chlorides (S also forms Ca and Mg sulfate). Cl and S, which are not bound by these elements, form gaseous emissions, namely, HCl and

SO_x . A molar ratio of $(K + Na)/(2S + Cl) > 1$ indicates a surplus of alkaline metals. Therefore, for high molar ratios of $(K + Na)/(2S + Cl)$ lower HCl and SO_x emissions have to be expected, since most of the S and Cl is expected to be bound in the ash.

A molar ratio of $2S/Cl > 1$ indicates an increased formation of alkaline sulfates, whereas a molar ratio of $2S/Cl < 1$ indicates the preferred formation of alkaline chlorides. As corrosion-related problems on heat exchanger surfaces are depending on the Cl content of the ash deposits, a low molar ratio of $2S/Cl$ increases the risk of corrosion.

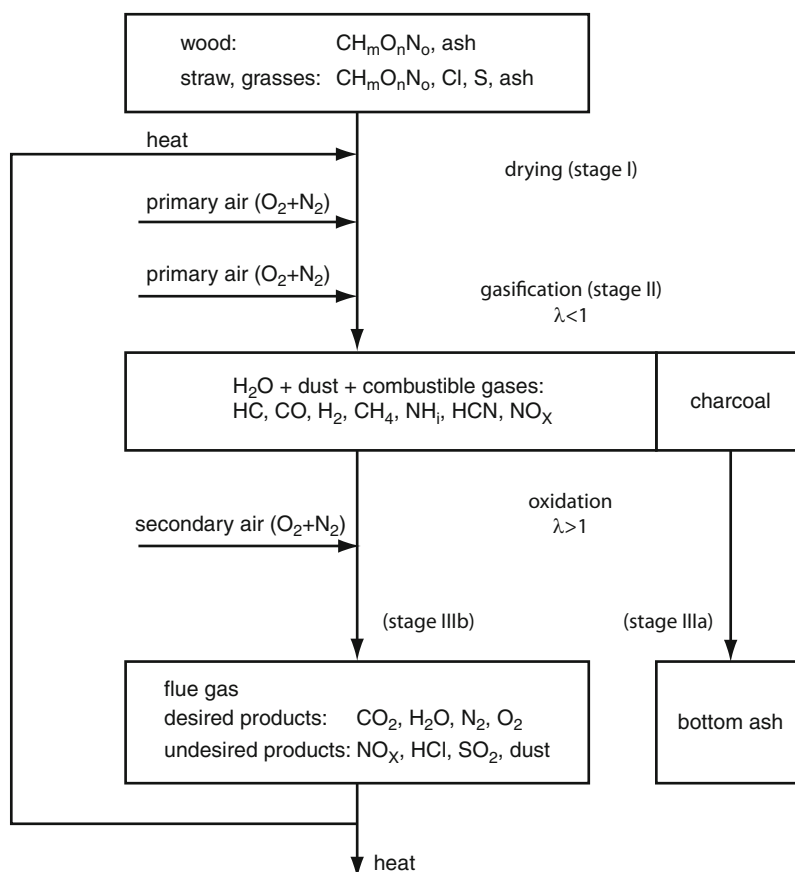
The elements K, Na, Zn, and Pb are the most relevant aerosol-forming elements in biomass fuels. With increasing concentration of these elements in a biomass fuel the probability of the release of ash-forming elements during combustion rises and therefore aerosol formation as well as deposit formation increase as well. However, the formation of ash vapors during combustion is not proportional to the concentration of these elements in the fuel since

chemical reactions with other elements (e.g., Si) as well as the gaseous atmosphere and the combustion temperature significantly influence the release behavior.

Combustion Principles

In the ideal case, combustion represents a complete oxidation of the solid organic part of the fuel into the gases CO_2 and H_2O . This conversion occurs in different stages or steps, starting with the drying of the fuel particles followed by pyrolysis/gasification and the final oxidation of the charcoal and the flue gases (Fig. 4).

In order to achieve a combustion that is as efficient as possible, each of these combustion steps must be



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 4
Process of biomass combustion – principle [12]

optimized within the combustion technology implemented. After the step of drying (vaporizing H_2O) the main controlling parameter of the combustion process is the ratio between the amount of air added and the amount of air (oxygen) necessary for a complete combustion of the combustible parts of the fuel, the λ (excess air) factor.

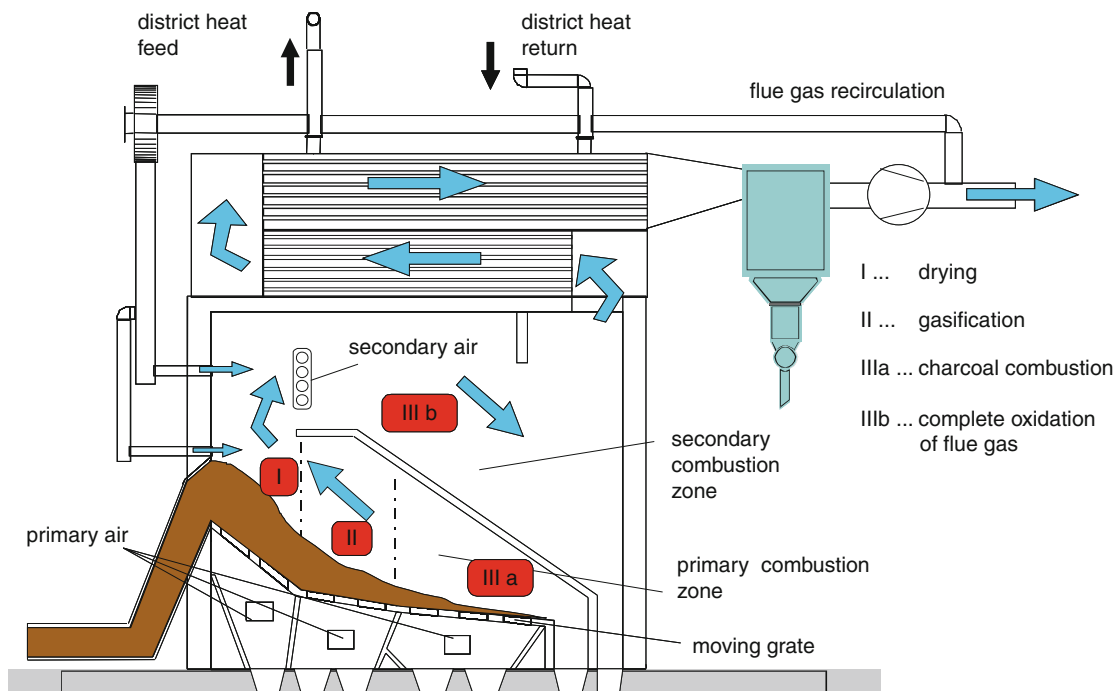
At λ below 1, incomplete oxidation of the fuel (gasification) takes place and only a part of the energy of the fuel is converted into thermal energy. Adding too much air ($\lambda \gg 1$) will cool down the process, leading to incomplete combustion and thermal losses. Thus the theoretical optimum of the combustion process is at a λ equal to 1. But in reality this point is difficult to obtain due to mixing constraints between the fuel, flue gas and the air added. Thus, depending on the combustion technology utilized, a total λ between 1.1 to 1.8 in large-scale and 1.5 to 2.0 in medium-scale applications is common in order to achieve a complete combustion.

A lower total λ can be achieved by separating the combustion stages into different locations in the furnace and thereby increasing the retention time for reactions and also the possibility of optimized control.

This type of separation, the so-called staged combustion, is shown in Fig. 5, where the drying (I), pyrolysis/gasification (II) and the oxidation of the char (III a) take place in different zones on and above the grate (primary combustion chamber). Then the flue gases are completely oxidized by addition of secondary air in the secondary combustion chamber (III b).

Industrial Combustion Technologies

The characteristics and the quality of biomass as a fuel vary widely, depending on the kind of biomass and the pretreatment technologies applied. For example, the moisture content of the fuel as fed into the furnace may vary from 25 to 60 wt% (w.b.) (bark, sawmill by-products) or drop below 10 wt% (w.b.) (pellets, dry wood processing residues). Also, the ash sintering temperatures of biofuels may extend over a wide range (600–1,200°C) [14, 15] and the particle shapes and sizes can be manifold. Fuel quality can be influenced and improved by suitable (costly) pretreatment technologies, like drying, chopping, and pelletizing.



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 5

Process of biomass combustion – allocation of the different stages of combustion in a grate furnace [12, 13]

The selection and design of a biomass combustion system is mainly determined by the characteristics of the fuel to be used, the local environmental legislation, as well as by the costs and the performance of the equipment. Another important factor is the size of the plant and the decision whether a heat only or a CHP application should be implemented.

Furthermore, the fuel characteristics can be influenced in order to fulfill the technological and environmental requirements of a given combustion technology by appropriate pretreatment systems. The most suitable technology package therefore can vary from case to case. Generally, due to *economy-of-scale* effects concerning the complexity of the fuel-feeding system, the combustion technology, and the flue gas cleaning system, large-scale systems usually use low-quality fuels (with inhomogeneous fuel characteristics concerning e.g., moisture content, particle size, and ash melting behavior), while high-quality fuels are necessary for small-scale systems in most cases.

While wood is a suitable fuel regardless of the size of the combustion plant, herbaceous biomass is almost entirely used in medium and large-scale plants. The same is true for urban waste wood and demolition wood, in particular due to the need for an efficient flue gas cleaning for the abatement of toxic pollutants (e.g., heavy metals, chlorine compounds).

Accordingly, biomass combustion technologies are divided into

- Small-scale (domestic) combustion, defined as units used for heating or cooking up to a capacity of about 100 kW
- Medium and large-scale industrial combustion, defined as systems used for process heat production, district heating as well as combined heat and power production (CHP) in units larger than 100 kW up to several hundred MW_{th}.

Medium and large-scale combustion systems are typically equipped with mechanical or pneumatic fuel-feeding systems and process control systems supporting fully automatic system operation. In general, the larger the combustion unit the more flexible it becomes regarding the quality of the biofuels used. Thus solid biofuels used in medium and large-scale biomass combustion units comprise not only wood, but also bark, energy crops, agricultural

waste products, urban waste wood, and in some cases mixtures of these.

In principle, the following combustion technologies can be distinguished (Fig. 6):

- Fixed-bed combustion
- Bubbling fluidized bed combustion
- Circulating fluidized bed combustion
- Dust combustion

The basic principles of these technologies are shown in Fig. 6 and described below [13, 16].

Fixed-bed combustion systems include underfeed stokers and grate furnaces. Primary air passes through a fixed bed, in which drying, gasification, and charcoal combustion takes place. The combustible gases produced are burned after secondary air has been added, usually in a combustion zone separated from the fuel bed.

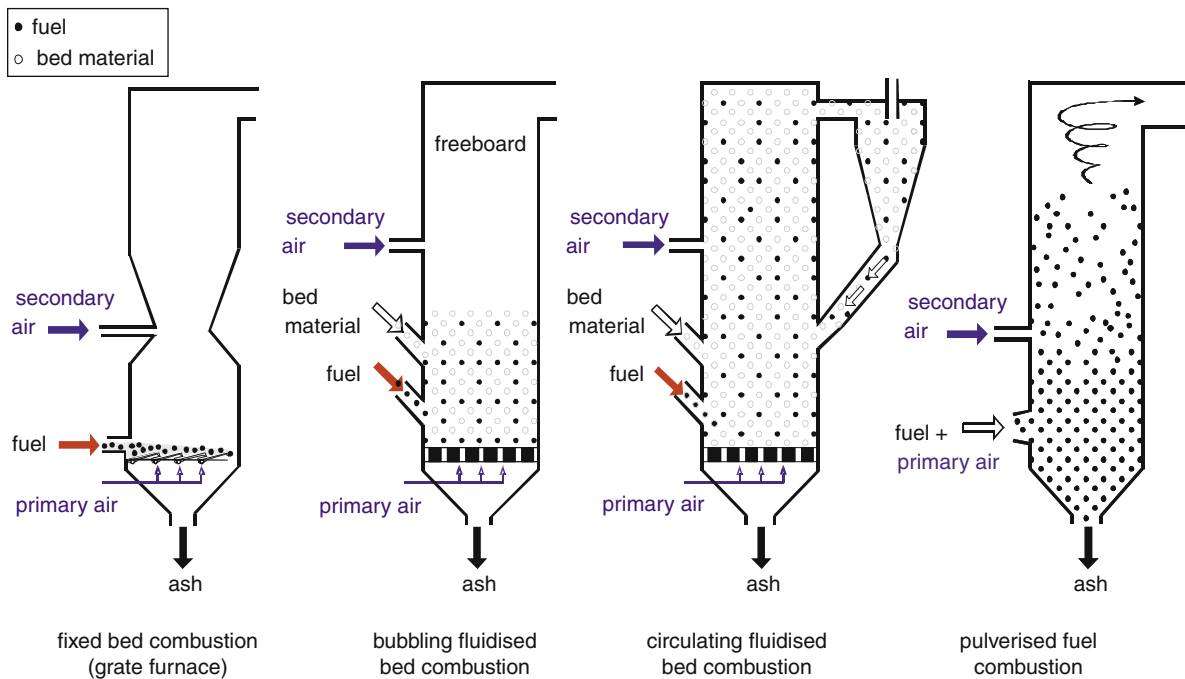
Within a fluidized bed furnace, biomass fuel is burned in a self-mixing suspension of gas and solid-bed material into which combustion air enters from below. Depending on the fluidization velocity, bubbling fluidized bed and circulating fluidized bed combustion can be distinguished.

Dust combustion is suitable for fuels available as small particles (average diameter smaller 2 mm). A mixture of fuel and primary combustion air is injected into the combustion chamber where the combustion takes place while the fuel is in suspension. The gas burnout is achieved after secondary air addition. Variations of these basic technologies are also available (e.g., combustion systems with spreader stokers and cyclone burners).

Fixed-Bed Furnaces

Below selected fixed-bed furnaces are discussed in detail.

Underfeed Stokers In underfeed stoker units the fuel is feed into the combustion chamber by screw conveyors from below and is transported upward on an inner or outer grate. Outer grates are more common in modern combustion plants because they allow for more flexible operation and an automatic ash removing system can be attained more easily. Primary air is supplied through the grate, secondary air usually at the entrance to the secondary combustion chamber.



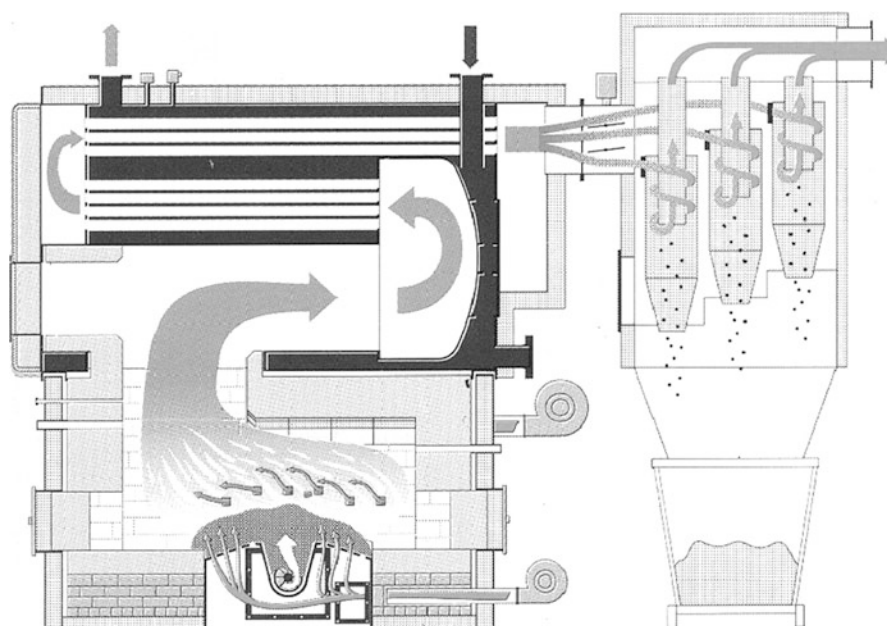
Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 6
Combustion technologies for biomass [16]

The underfeed technology has been specially developed for fine-grained biomass fuels (below 50 mm) like wood shavings, pellets, or sawdust and is only suitable for fuels with low ash content (because of the limited ash transport from the grate) and with low mineral or metal impurities (as they may block the screw feeders). Moreover, sintered or melted ash particles covering the upper surface of the fuel bed can cause problems in underfeed stokers due to unstable combustion conditions when the fuel and the air are breaking through the ash-covered surface.

Because of the technical limitation of supplying the fuel with screw conveyors, the limiting nominal boiler capacity for this type of units is about 6 MW_{th}. However, in this performance range the investments are typically lower than for other technologies (e.g., grate-fired combustion units) [2]. Another advantage of the underfeed stoker compared to moving grate units (see next section) is the continuous fuel feed which facilitates load regulation for low emissions. A schematic drawing of an underfeed biomass stoker combustion unit is shown in Fig. 7.

Moving Grate Furnaces In moving grate furnaces, the fuel is feed onto the grate either by pushing the fuel horizontally onto the grate or by spreading it onto the grate from above by a spreader stoker. Moving grate furnaces are distinguished by the way the grate is moving (e.g., inclined moving grates, horizontally moving grates, traveling grates, rotating grates, vibrating grates). All of these technologies have specific advantages and disadvantages, depending on fuel properties. Therefore, a careful selection and planning is necessary.

Moving grate furnaces are appropriate for biofuels with a high moisture content (up to 60%), varying particle sizes (with a downward limitation concerning the amount of fine particles in the fuel mixture), and high ash content (up to 50%). Mixtures of wood fuels can be used, but current technology does not allow for mixtures of wood fuels and straw, cereals and grass, due to their different combustion behavior, low moisture content, and low ash melting temperatures. A good and well-controlled grate is designed to guarantee a homogeneous distribution of the fuel and the bed of embers over the whole grate surface. This is important



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 7
Underfeed stoker furnace [17]

to guarantee a uniform primary air supply over the different grate areas. Inhomogeneous air supply may cause slagging, high fly-ash amounts, and may increase the amount of excess oxygen needed for a complete combustion. Furthermore, the transport of the fuel over the grate must be as smooth and homogeneous as possible in order to keep the bed of embers calm and homogeneous, to avoid the formation of “holes”, and to avoid as far as possible the elutriation of fly ash and unburned particles.

The technology needed to achieve these aims includes continuously moving grates, an elaborated control system of the bed of embers (e.g., by infrared beams), and frequency-controlled primary air fans for the different grate sections. The primary air supply divided into physically separated sections below the grate is necessary to be able to adjust the specific air amounts to the requirements of the zones where drying, gasification, and charcoal combustion prevail. These separately controllable primary air supplies also allows a smooth operation of grate furnaces at partial loads of up to a minimum of about 25% of the nominal furnace load and control of the primary air ratio needed (to secure a reducing atmosphere in the primary combustion chamber necessary for low

NO_x operation). Moreover, grate systems can be water-cooled to avoid slagging and to extend the lifetime of the materials.

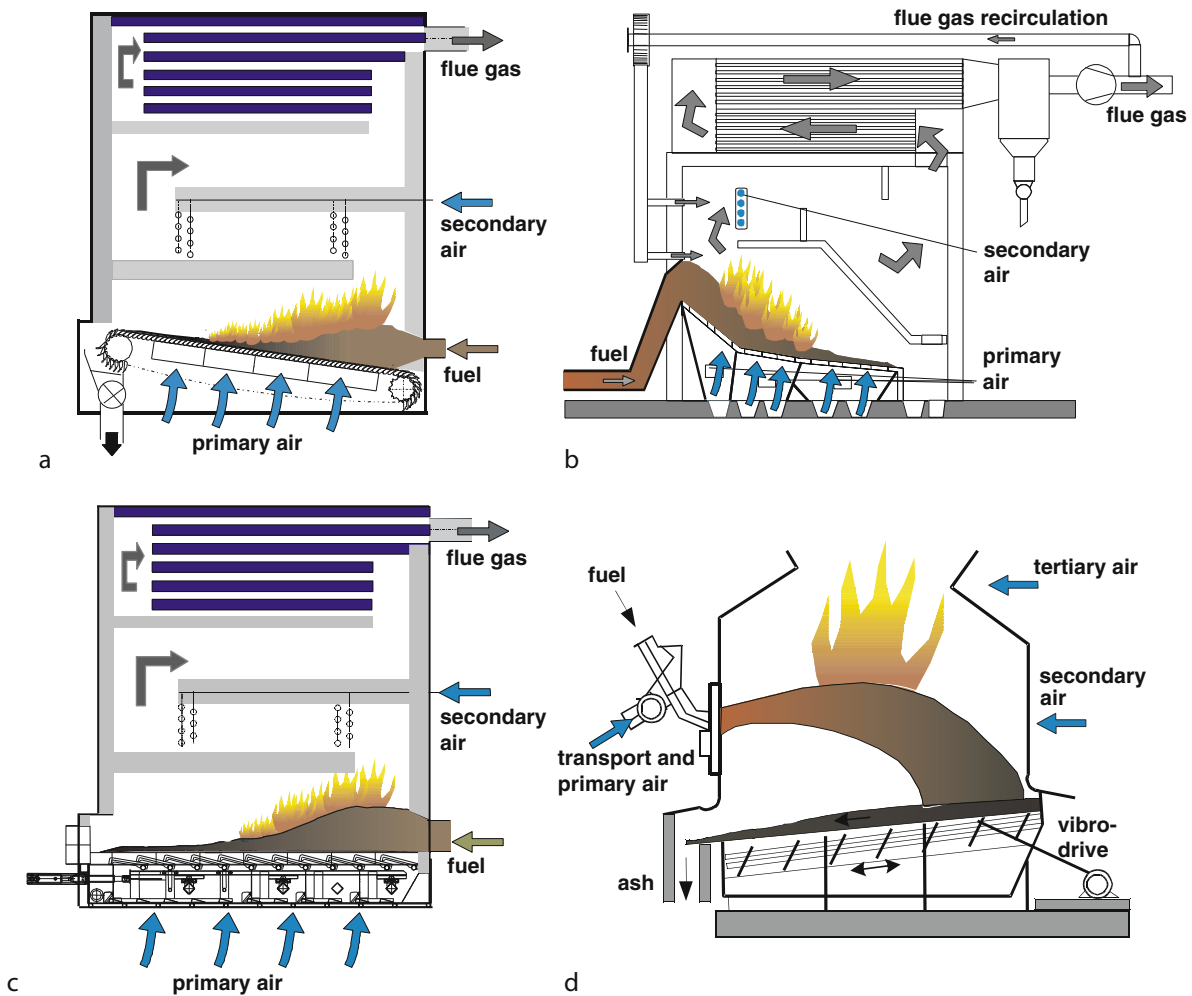
Another important aspect of grate furnaces is that a staged combustion should be obtained by separating the primary and the secondary combustion chambers in order to avoid back-mixing of the secondary air and to separate gasification and oxidation zones. Because the mixing of air and flue gas in the primary combustion chamber is not optimal due to the low turbulence necessary for a calm bed of embers on the grate, the geometry of the secondary combustion chamber and secondary air injection must guarantee a mixture of flue gas and air that is as complete as possible. The better the mixing quality between flue gas and secondary combustion air, the lower the amount of excess oxygen necessary for complete combustion and the higher the efficiency. The mixing effect can be improved with relatively small channels where the flue gas reaches high velocities and where the secondary air is injected at high speed via nozzles that are well distributed over the cross section of this channel. Other means of achieving a good mixture of flue gas and secondary air are combustion chambers with a vortex or cyclone flow.

In order to achieve adequate temperature control in the furnace, flue gas recirculation and water-cooled combustion chamber walls are used. Combinations of these technologies are also possible. Water cooling has the advantage of reducing the flue gas volume, impeding ash sintering on the furnace walls and usually extending the lifetime of insulation bricks. If only dry biomass fuels are used, combustion chambers with steel walls can also be applied (without insulation bricks). Wet biomass fuels need combustion chambers with insulation bricks operating as heat accumulators and buffering moisture content and combustion

temperature fluctuations in order to ensure a good burnout of the flue gas.

Below, different types of moving grate constructions are discussed in more detail.

Traveling grate furnaces consist of grate bars mounted on an endless belt (like an escalator) moving through the combustion chamber (Fig. 8a). The fuel is supplied at one end of the combustion chamber onto the grate (e.g., by screw conveyors) or is distributed over the grate by spreader-stokers injecting the fuel into the combustion chamber. The fuel bed itself does not move, but is transported through the combustion



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 8

A traveling, an inclined moving, a horizontally moving, and a vibrating grate furnace (a) traveling grate [12] (b) inclined moving grate [13] (c) horizontally moving grate [17] (d) vibrating grate [16]

chamber by the grate, contrary to moving grate furnaces where the fuel bed is moved over the grate. At the end of the combustion chamber the grate is cleaned of ash and dirt while the belt turns around (automatic ash removal). On the way back, the grate bars are cooled by primary air in order to avoid overheating and to minimize wear. The speed of the traveling grate is continuously adjustable in order to achieve complete charcoal burnout. The advantages of traveling grate systems are uniform combustion conditions for wood chips and pellets and low emissions of particulate matter, due to the stable and almost unmoving bed of embers. In addition, the maintenance or replacement of grate bars is easy to handle. However, the fact that the bed of embers is not stoked results in a longer burnout time and also may cause bridging of fuel and/or ash particles. Higher primary air input is needed for complete combustion (which implies a lower NO_x reduction potential by primary measures). Moreover, nonhomogeneous biomass fuels imply the danger of bridging and uneven distribution on the grate surface due to lack of mixing. This disadvantage can be avoided by spreader-stokers, which cause a mixing of the fuel bed by the fuel-feeding mechanism applied.

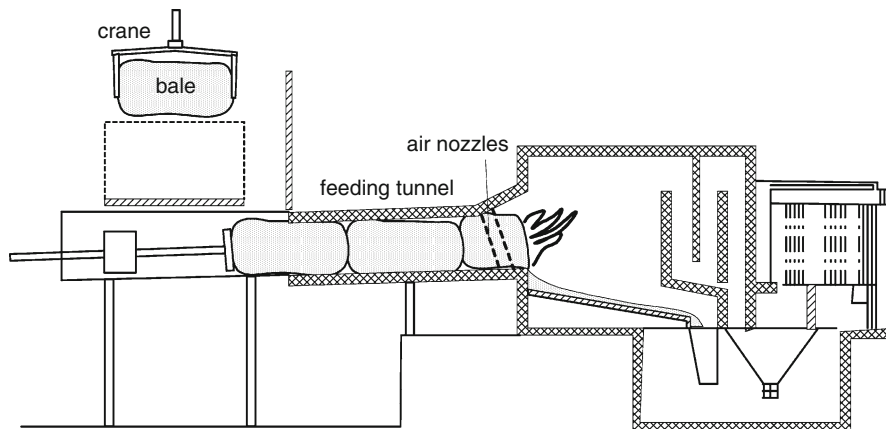
Inclined moving grates have an inclined grate consisting of fixed and movable rows of grate bars (Fig. 8b). By alternating horizontal forward and backward movements of the movable sections, the fuel is transported along the grate. Thus unburned and burned fuel particles are mixed, the surfaces of the fuel bed are renewed, and a more even distribution of the fuel over the grate surface can be achieved (which is important for a uniform primary air distribution across the fuel bed). Usually, the whole grate is divided into several grate sections, which can be moved at different speeds according to the different stages of combustion. The movement of the grate bar is achieved by hydraulic cylinders. The grate bars themselves are made of heat-resistant steel alloys. They are equipped with small channels in their side walls for primary air supply and should be as narrow as possible in order to distribute the primary air across the fuel bed as well as possible. In moving grate furnaces, a wide variety of biofuels can be burned. Air-cooled moving grate furnaces use primary air for cooling the grate and are suitable for wet bark, sawdust, and wood chips, while

water-cooled moving grate systems are recommended for dry biofuels or biofuels with low ash-sintering temperatures. In contrast to traveling grate systems, the correct adjustment of the moving frequency of the grate bars is more complex. If the moving frequencies are too high, high concentrations of unburned carbon in the ash or insufficient coverage of the grate will result. Infrared beams situated over the different grate sections allow for adequate control of the moving frequencies by checking the height of the bed. Ash removal takes place under the grate in dry or wet form and a fully automatic operation of the entire system is common.

Horizontally moving grates have a completely horizontal fuel bed (Fig. 8c). This is achieved by the diagonal positioning of the grate bars. This has the advantage that it impedes uncontrolled gravity-induced fuel movements on the grate and increases the stoking effect of the grate movements, thus leading to a very homogeneous distribution of material on the grate surface and impeding slag formation because of hot spots. A further advantage is that the overall height can be reduced. In order to prevent ash and fuel particles from falling through the grate bars, horizontally moving grates should be preloaded so that there is no free space between the bars.

Vibrating grate furnaces consist of a declined finned tube wall placed on springs (Fig. 8d). Fuel is fed into the combustion chamber by spreaders, screw conveyors, or hydraulic feeders. Depending on the combustion process, two or more vibrators transport fuel and ash toward the ash removal unit. Primary air is fed through the fuel bed from below through holes located in the ribs of the finned tube walls. Due to the vibrating movement of the grate at short periodic intervals, the formation of larger slag particles is inhibited. This is the reason why this grate technology is especially applied with fuels showing sintering and slagging tendencies (e.g., straw, waste wood). The disadvantages are the high fly-ash emissions caused by the vibrations, the higher CO emissions due to the periodic disturbances of the fuel bed, and an incomplete burnout of the bottom ash because fuel and ash transport are more difficult to control.

The *cigar burner* is a technology developed for straw and cereal combustion in Denmark (Fig. 9). Straw and cereal bales are delivered in a continuous process



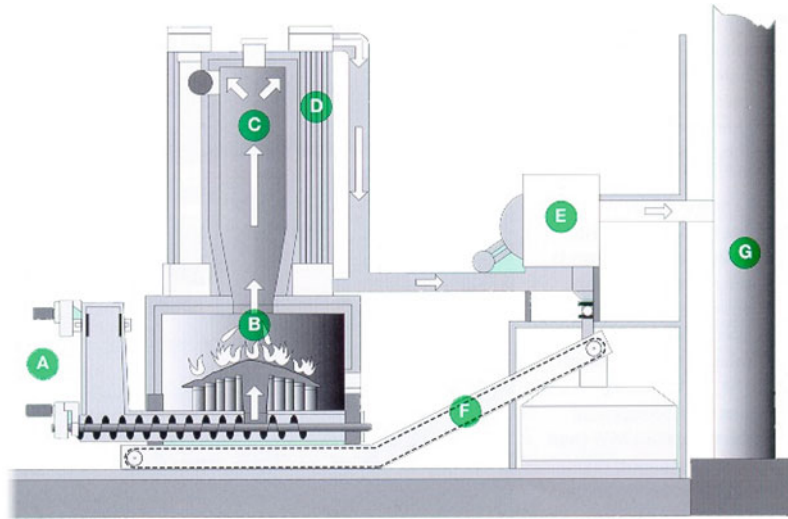
Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 9
Cigar burner [16]

by a hydraulic piston through a feeding tunnel on a water-cooled grate. Upon entering the combustion chamber gasification of the fuel starts and combustion of the charcoal follows while moving the unburned material over the grate. Grate and furnace temperature control is very important for straw and cereal combustion, due to their low ash melting point and the high adiabatic temperature of combustion caused by the low water content. The combustion chambers must, therefore, be cooled either by water cooled walls or by flue gas recirculation (or by a combination). Furnace temperatures should not exceed 900°C for normal operation. Furthermore, straw and cereal combustion causes very fine and light fly ash particles as well as aerosols to be formed from condensed alkali chlorides/sulfates. This results in the necessity of a regular heat exchanger cleaning system to avoid ash deposits as far as possible. Systems for shredded or cut straw also exist and are operated in a similar way to the technology described. Only the fuel preparation is different. Smaller pieces of straw, slices of straw bales, or shredded straw is preferable to whole bale combustion because smaller particles allow a better combustion control along the grate. Semicontinuous systems like whole bale combustion furnaces where the bales are fed in batch-wise operation into the furnace are not recommended due to the temperature and CO peaks caused when a new bale is delivered. The state-of-the-art process control systems are not able to prevent this unsteady combustion.

Underfeed rotating grate combustion is a Finnish biomass combustion technology that makes use of conical grate sections that rotate in opposite directions and are supplied with primary air from below (Fig. 10). As a result wet and burning fuels are well mixed, which makes the system adequate for burning very wet fuels such as bark, sawdust, and wood chips (with a moisture content up to 65 wt% [w.b.]). The combustible gases formed are burned out with secondary air in a separate horizontal or vertical combustion chamber. The horizontal version is suitable for generating hot water or steam in boilers with a nominal capacity between 1 and $10 \text{ MW}_{\text{th}}$. The vertical version is applied for hot water boilers with a capacity of $1\text{--}4 \text{ MW}_{\text{th}}$. The fuel is fed to the grate from below by screw conveyors (similar to underfeed stokers), which makes it necessary to keep the average particle size below 50 mm. Underfeed rotating grate combustion plants are also capable of burning mixtures of solid wood fuels and biological sludge. The system is computer controlled and allows fully automatic operation.

Fluidized Bed Combustion

Fluidized bed (FB) combustion systems have been applied since 1960 for combustion of municipal and industrial wastes. Since then, over 300 commercial installations have been built worldwide. Regarding technological applications, bubbling fluidized beds (BFB) and circulating fluidized beds (CFB) are distinguished.



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 10

Rotating grate underfeed stoker. (Explanations: 1 fuel feed, 2 rotating grate, 3 bottom of the cone, 4 primary air, 5 air control, 6 ash disposal, 7 ash screw conveyor, 8 burn out zone, 9 secondary air)

A fluidized bed consists of a cylindrical vessel with a perforated bottom plate filled with a suspension bed of hot, inert, and granular material. The common bed materials are silica sand and dolomite. The bed material represents 90–98% of the mixture of fuel and bed material. Primary combustion air enters the furnace from below through the air distribution plate and fluidizes the bed so that it becomes a seething mass of particles and bubbles. The intense heat transfer and mixing provide good conditions for a complete combustion with low excess air demand (λ between 1.1 and 1.2 for CFB plants and between 1.3 and 1.4 for BFB plants). The combustion temperature must be kept low (usually between 800°C and 900°C) in order to prevent ash sintering in the bed. This can be achieved by internal heat exchanger surfaces, by flue gas recirculation, or by water injection (in fixed-bed combustion plants combustion temperatures are usually 100–200°C higher than in FB units).

Due to the good mixing achieved, FB combustion plants can deal flexibly with different fuel mixtures (e.g., mixtures of wood and straw) but are limited when it comes to fuel particle size and impurities contained in the fuel. Therefore, an appropriate fuel pretreatment system covering particle size reduction and separation of metals is necessary for fail-safe operation. Usually a particle size below 40 mm is

recommended for CFB units and below 80 mm for BFB units. Moreover, partial load operation of FB combustion plants is limited due to the need of bed fluidization.

Fluidized bed combustion systems need a relatively long start-up time (up to 15 h) for which oil or gas burners are used. Low NO_x emissions can be achieved owing to good air staging, good mixing, and a low requirement of excess air. Moreover, the utilization of additives (e.g., limestone addition for sulfur capture) works well due to the good mixing behavior. The low excess air quantities necessary increase combustion efficiency and reduce the flue gas volume flow. This makes FB combustion plants especially interesting for large-scale applications (normal boiler capacity above 30 MW_{th}). For smaller combustion plants the investment and operating costs are usually too high in comparison to fixed-bed systems. One disadvantage is that they cause high dust loads to be entrained with the flue gas, which makes efficient dust precipitators and boiler cleaning systems necessary. Bed material is also lost with the ash, making it necessary to periodically add new material to the plant.

- Bubbling fluidized bed combustion (BFB) furnaces start to be of interest for plants with a nominal boiler capacity of over 20 MW_{th} . In BFB furnaces

(Fig. 6), a bed material is located in the bottom part of the furnace. The primary air is supplied via a nozzle distributor plate and fluidizes the bed. The bed material is usually silica sand about 1.0 mm in diameter. The fluidization velocity of the air varies between 1.0 and 2.5 m/s. The secondary air is introduced through several inlets in the form of groups of horizontally arranged nozzles at the beginning of the upper part of the furnace (called freeboard) to ensure a staged-air supply to reduce NO_x emissions. Biofuel should not be feed onto, but into, the bed by inclined chutes from fuel hoppers because of the higher reactivity of biomass. The fuel amounts only to 1–2% of the bed material and the bed must be heated (internally or externally) before the fuel is introduced. The advantage of BFB furnaces is their larger flexibility concerning particle size and moisture content of the biomass fuels in comparison to CFB units. Furthermore, it is also possible to use mixtures of different kinds of biomass or to co-fire them with other fuels. One disadvantage (the difficulties at partial load operation) may be solved by splitting or staging the bed.

- By increasing the fluidizing velocity to 5–10 m/s and using smaller sand particles (0.2–0.4 mm in diameter) a circulating fluidized bed combustion (CFB) system is achieved (Fig. 6). The sand particles will be carried along with the flue gas, separated in a hot cyclone or a U-beam separator, and feed back into the combustion chamber (Fig. 6). The bed temperature (800–900°C) is controlled by external heat exchangers cooling the recycled sand, or by water-cooled walls. The higher turbulence in CFB furnaces leads to a better heat transfer and a very homogeneous temperature distribution within the bed. This is of advantage for stable combustion conditions, the control of air staging, and the placement of heating surfaces right in the upper part of the furnace. The disadvantages of CFB furnaces are their large size and therefore high price, the considerable dust load in the flue gas leaving the sand particle separator, the high loss of bed material in the ash, and the small fuel particle size required (between 0.1 and 40 mm in diameter) often requiring a high investment in fuel pretreatment. Moreover, their operation at partial

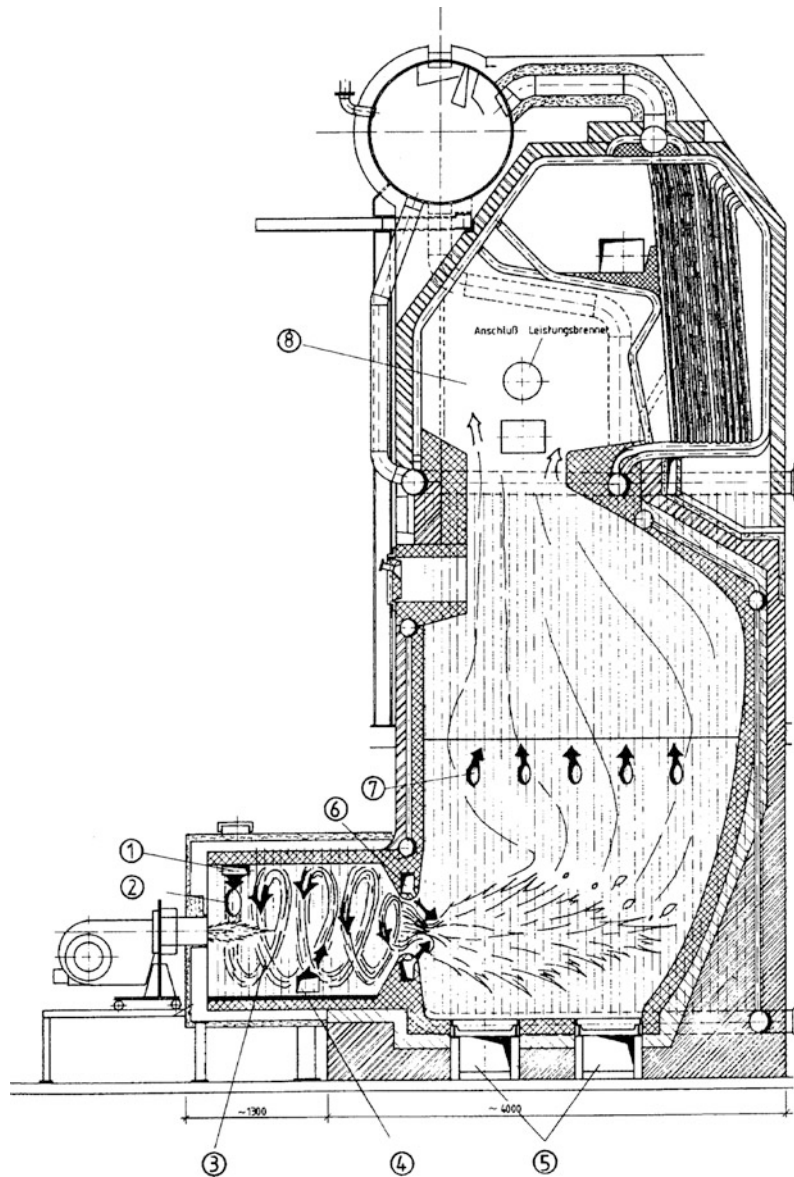
load is problematic. In view of their high specific heat transfer capacity, CFB furnaces start to be of interest for plants of more than 30 MW_{th} , due to their higher combustion efficiency and the lower flue gas flow produced (boiler and flue gas cleaning units can be dimensioned smaller).

Dust Combustion

In dust combustion systems, fuels like sawdust and fine shavings are pneumatically injected into the furnace (Fig. 11). The transportation air is used as primary air. Start-up of the furnace is achieved by an auxiliary burner. When the combustion temperature reaches a certain value, biomass injection starts and the auxiliary burner is shut down. Fuel quality in dust combustion systems needs to be quite constant. A maximum fuel particle size of 10–20 mm must be maintained and the fuel moisture content should normally not exceed 20 wt% (w.b.). The fuel feeding system needs to be controlled very carefully and forms a key technological unit within the overall system due to the explosion-like gasification of the fine and small biomass particles. Fuel/air mixtures are usually injected tangentially into the cylindrical furnace muffle to establish a rotational flow (usually a vortex flow). The rotational motion can be supported by flue gas recirculation in the combustion chamber. The muffle should be water cooled due to the high energy density at the furnace walls and the high combustion temperature. Fuel gasification and charcoal combustion take place at the same time because of the small particle size. Therefore, quick load changes and efficient load control can be achieved.

Besides muffle furnaces, cyclone burners for wood dust combustion are also in use. Depending on the design of the cyclone and the location of fuel injection, the residence time of the fuel particles in the furnace (their burnout) can be controlled well and, if staged combustion is used, also NO_x formation can also be kept low.

A disadvantage of muffle furnaces and cyclone burners is that insulation bricks wear out quickly due to thermal stress and erosion. Other dust combustion systems are thus being built without rotational flow, where dust injection is conducted



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 11

Dust combustion system (muffle furnace) in combination with a water-tube steam boiler [16]. (Explanations: 1 primary air supply, 2 fuel feed, 3 gasification and partial combustion, 4 flue gas recirculation, 5 ash disposal, 6 secondary air supply, 7 tertiary air supply, 8 water tube boiler)

without a swirl in the same way as in a furnace burning fuel oil or natural gas.

Summary

In general, BFB and CFB furnaces show lower CO and NO_x emissions due to more homogeneous and

therefore more controllable combustion conditions, while fixed-bed furnaces usually emit less particulate matter and show a better burnout of the fly ash [18, 19].

Table 3 gives a summary of solid biomass combustion technologies and their typical applications and fuel specifications, and Table 4 shows the advantages

Biomass Energy Heat Provision in Modern Large-Scale Systems. Table 3 Summary of solid biomass combustion technologies with typical applications and fuels

Technology	Typical size range	Fuels	Ash content (%)	Moisture content (%)
Underfeed stoker furnaces	10 kW–6.0 MW	Wood chips, wood residues	<2	5–50
Moving grate furnaces	500 kW–50 MW	All wood fuels and most biomass	<10	5–60
Underfeed stoker with rotating grate	2–20 MW	Wood chips, high water content	<10	30–65
Straw furnaces	100 kW–10 MW	Straw bales with bale shredders	<5	<20
Cigar burner	3–5 MW	Straw bales	<5	<20
Dust combustor, or cyclone furnaces	1–10 MW	Various biomass, (dP < 5 mm)	<2	<20
Bubbling fluidized bed	20–50 MW	Various biomass, (dP < 80 mm)	<10	5–60
Circulating fluidized bed	30–100 MW	Various biomass, (dP < 40 mm)	<10	5–60

dP Fuel particle diameter

Biomass Energy Heat Provision in Modern Large-Scale Systems. Table 4 Summary of advantages and disadvantages of different solid biomass combustion technologies

Advantages	Disadvantages
<i>Underfeed stokers</i>	
Low investment costs for plants < 6 MW _{th}	Suitable only for biofuels with low ash content and high ash melting point (wood fuels) Low flexibility concerning particle size as well as concerning mineral and metal impurities in the fuel
Simple and good load control due to continuous fuel feeding	
Low emissions at partial load operation due to good fuel dosing	
<i>Moving grate furnaces</i>	
Low investment costs for plants < 20 MW _{th}	No mixing of wood fuels and herbaceous fuels possible
Low operating costs	Efficient NO _x reduction requires special technologies
Low dust load in the flue gas	High excess air ratio (1.3–1.6) decreases efficiency
Less sensitive to slagging than fluidized bed furnaces	Combustion conditions not as homogeneous as in fluidized bed furnaces
Many options in terms of fuel particle size and moisture content	Low emissions at partial load operation are difficult to achieve
<i>Dust combustion</i>	
Low excess air ratio (1.25–1.4) is possible which increases efficiency	Particle size of biofuel is limited (<10–20 mm)
High NO _x reduction by efficient air staging and mixing possible if cyclone or vortex burners are used	High wear of the insulation brickwork if cyclone or vortex burners are used
Very good load control and fast alternation of load possible	An extra start-up burner is necessary

Biomass Energy Heat Provision in Modern Large-Scale Systems. Table 4 (Continued)

Advantages	Disadvantages
<i>BFB furnaces</i>	
No moving parts in the hot combustion chamber	High investment costs, interesting only for plants >20 MW _{th}
NO _x reduction by air staging works well	High operating costs
High flexibility concerning moisture content and type of biomass fuels used (fuel mixing possible)	Low flexibility with regard to particle size (<80 mm)
Low excess air ratio (1.2–1.25) raises efficiency and decreases flue gas flow	High dust load in the flue gas
	Operation at partial load requires special technology
	Medium sensitivity concerning ash slagging
	Loss of bed material with the ash
	Medium erosion of heat exchanger tubes in the fluidized bed
<i>CFB furnaces</i>	
No moving parts in the hot combustion chamber	High investment costs, interesting only for plants > 30 MW _{th}
NO _x reduction by air staging works well	High operating costs
High flexibility concerning moisture content and type of biomass fuels used (fuel mixing possible)	Low flexibility with regard to particle size (<40 mm)
Homogeneous combustion conditions in the furnace if several fuel injectors are used	High dust load in the flue gas
High specific heat transfer capacity due to high turbulence	Partial-load operation requires a second bed
Use of additives easy	High sensitivity concerning ash slagging
Very low excess air ratio (1.05–1.1) raises efficiency and decreases flue gas flow	Loss of bed material with the ash
	Medium erosion of heat exchanger tubes in the furnace

and disadvantages of the different combustion technologies discussed above.

Combustion-Based Power Generation Processes

Electric power production is generally implemented in larger applications such as industrial combustion units or district heating systems. The status of power generation from biofuel combustion is limited to closed thermal cycles. Open processes such as internal combustion engines or direct gas turbines are still in the research stage and not applicable so far mainly due to limitations in separating particles and particle-forming gaseous species (e.g., KCl, K₂SO₄) from the hot flue gas.

In a closed thermal cycle, the combustion of the fuel and the power generation cycle are separated by a heat

transfer from the hot flue gas to a process medium used in a secondary cycle. This separation between the fuel and the power-producing engine prevents undesired elements in the fuel and flue gas from causing damage to the engine.

The processes and engine types used or under development today are shortly described here (see [2, 9, 10, 20, 21]).

The available technologies for power production from biomass combustion comprise:

- *Steam turbines* (ST) used as expansion engines in the Rankine cycle with water as a process medium; the water is evaporated under pressure and superheated in heat exchangers in the boiler section of the combustion plant

- *Steam piston engines (SPE)* used in the Rankine cycle with or without superheating and transferring the volume work into mechanical work by a piston [22]
- Steam turbines used in *organic Rankine cycles* (ORC) with evaporation of an organic medium in a tertiary cycle separated from the heat production (the combustion heat is transferred to a thermal oil in the boiler which is feed to an external evaporator for the organic medium with a lower boiling temperature than water) [2];
- *Stirling engines* (STE) (indirectly fired gas engines) which are driven by a periodic heat exchange from flue gas to a gaseous medium such as air, helium, or hydrogen [23, 24]
- *Micro-gas turbines* (MGT) using a hot gas cycle with a turbine as an expansion engine.

The most important technical data for power production from biomass combustion are shown in Table 5. The total efficiency indicated within this table is calculated according to Eq. 1.

$$\eta_{\text{tot}} = \frac{P_{\text{el(produced)}} - P_{\text{el(auxiliary)}} + P_{\text{th}}}{P_{\text{fuel input(NCV)}}} \quad (1)$$

The electric efficiency of the plant is calculated according to Eq. 2.

$$\eta_{\text{el-plant}} = \frac{P_{\text{el(produced)}} - P_{\text{el(auxiliary)}}}{P_{\text{fuel input(NCV)}}} \quad (2)$$

Both equations are based on the power supplied with the fuel based on its net calorific value (NCV). The auxiliary electric power is the power needed for the operation of the power or CHP plant and has to be subtracted from the gross electric power produced in order to achieve the net electric power of the plant, which is of relevance for the efficiency calculations stated.

In the column “recommended operation” the best way of operating the plant is shown, i.e., if the plant should be mainly operated for the production of heat (h) or heat and electric power (h/p). The remaining columns give an insight into the current stage of development and experience with the different technologies.

Steam turbines and steam piston engines are available as tested technology for power production through biomass combustion. While steam engines are used with capacities ranging from below 0.1–1.5 MW_{el}, steam turbines exist from 150 kW_{el} upward. The largest purely biomass-fired CHP plant today is equipped with steam turbines and has a nominal electric capacity of 240 MW [1]. Large steam turbine plants are operated with water tube boilers and superheaters making high steam parameters and the use of multi-stage turbines possible. Furthermore, process measures such as feed water preheating and intermediate tapping are implemented for efficiency improvement. This allows electric efficiencies of about 25% to be achieved

Biomass Energy Heat Provision in Modern Large-Scale Systems. Table 5 Overview of CHP technologies used or under development for the production of electric power based on the combustion of solid biomass [2]

	P _{el} ^a (kW)	η _{el-plant} ^b (%)	η _{tot} ^c (%)	Recommended operation ^d	State of development ^e	Operating experience	Literature sources
ST	150–240,000	8–40	75–90	h/p	Marketable	Marketable	[1, 2, 25]
SPE	<100–1,500	8–16	75–85	h	Marketable	Marketable	[2]
ORC	200–3,000	10–20	75–85	h	Marketable	Marketable	[26–29]
STE	10–150	6.5–17	75–85	h	Demonstration	40,000 h	[30, 31]
MGT	up to 100	8–17	60–65	h/p	Demonstration	2,800 h	[32–36]

ST steam turbine, SPE steam piston engine, SSE steam screw-type engine, ORC organic Rankine cycle, STE Stirling engine, MGT micro gas turbine

^aElectric capacity

^bSee Eq. 1

^cSee Eq. 2

^dp Power-controlled operation recommended, h Heat controlled operation recommended

^ePossibilities: pilot status, demonstration status, marketable

in the size range of 5–10 MW_{el}. In plants around 50 MW_{el} and larger, the electric efficiency can rise to about 30% in cogeneration mode and more than 40% if operated as a condensing plant.

Small-scale steam plants (<2 MW_{el}) are built with fire tube boilers and hence operated at quite low steam parameters (below 32 bar, below 450°C), which significantly decrease their electric efficiency. Steam plants operated in CHP mode are mainly utilized for the production of process heat or base load district heat, which enables long continuous operation periods with high load.

Steam piston engines can be operated in single- or multistage mode, reaching electric efficiencies between 8–10% and 12–16%, respectively.

Organic Rankine cycles (ORC) are also available as an alternative to conventional steam plants in the range of 0.2 to about 3.0 MW_{el}. These can operate at lower temperatures and pressures, so that a combustion plant with a thermal oil boiler operating at atmospheric pressure can be applied instead of a costly high-pressure steam boiler. Furthermore, the ORC generator can be operated without a superheater because the expansion of the saturated steam of the organic medium leads to dry steam. Furthermore, similar or slightly higher efficiencies are achieved thanks to the availability of well-designed two-stage small-scale turbines for this specific application. ORC plants are a proven technology which has been implemented in biomass combustion plants since 1998 [29, 37].

An option for small-scale power production is the externally fired Stirling engine with air or helium as a medium in a gas-filled heat exchanger coupled to a biomass furnace. A critical component in such plants can be the gas-to-gas heat exchanger operated with hot flue gas from the biomass combustion. Chemically untreated wood is the most suitable fuel so far, since biomass fuels with high ash levels or increased Cl concentrations are a challenge for the heat exchanger. A critical and weak point of the Stirling engine process is also the long-term stability of the engine. At present, not more than 5,000 h have been obtained with a single engine.

Micro-gas turbine (MGT) processes are also being considered in R&D projects for small to medium-scale applications and reached an early demonstration stage. This process offers the possibility of the use of biomass

only as well as of the combined use of natural gas (internal combustion) and biomass (external combustion). The combined system offers good electric plant efficiencies and lower maximum temperatures at the air/flue gas heat exchanger compared to a biomass-only application. Moreover, they provide a high degree of automation. However, the technology is not yet proven and shows relatively high investment costs (no serial production yet). Due to thermal stresses in the high temperature air/flue gas heat exchanger only slow load changes are possible. Thus, future operating experiences will have to proof the technological maturity and applicability of such systems.

Emissions from Combustion and Ash-Related Problems

Gaseous Emissions

CO₂ is a major combustion product from all biomass fuels, originating from the carbon content in the fuel. However, these CO₂ emissions are regarded as being CO₂-neutral with respect to the anthropogenic greenhouse gas effect (when a sustainable agriculture/forestry is given) and this is considered to be one main environmental benefit of biomass combustion.

In the case of an incomplete combustion, pollutants such as CO, C_xH_y, PAH, tar, soot, unburned carbon, NH₃, and N₂O are formed. As shown above, an effective reduction of these pollutants is achieved by an optimized combustion process, providing good mixing between fuel and air, enough retention time (above 1.0 s) at high temperatures (above 850°C), and a low total λ. In modern automated furnaces with effective process control systems the concentrations of unburned pollutants can be reduced to levels close to zero (e.g., CO < 50 mg/Nm³ and C_xH_y < 5 mg/Nm³ at 11% O₂ [9]).

NO_x emissions from biomass combustion applications are mainly a result of complete oxidation of fuel nitrogen, both from gas-phase combustion and char combustion. Additional NO_x may be formed from nitrogen in the air under certain conditions. However, these reaction mechanisms are not considered to be of significant importance in most biomass combustion applications due to the limited combustion temperatures. The main nitric oxide emitted is NO to be converted to NO₂ within the atmosphere.

Figure 12 shows measured data of NO_x emissions (left) and the percentage of fuel N converted to NO_x (right) versus the N content in the fuel for different biomass fuels. The graphic clearly indicates that NO_x emissions increase with increasing N content in the fuel while the rate of fuel N converted to NO_x decreases.

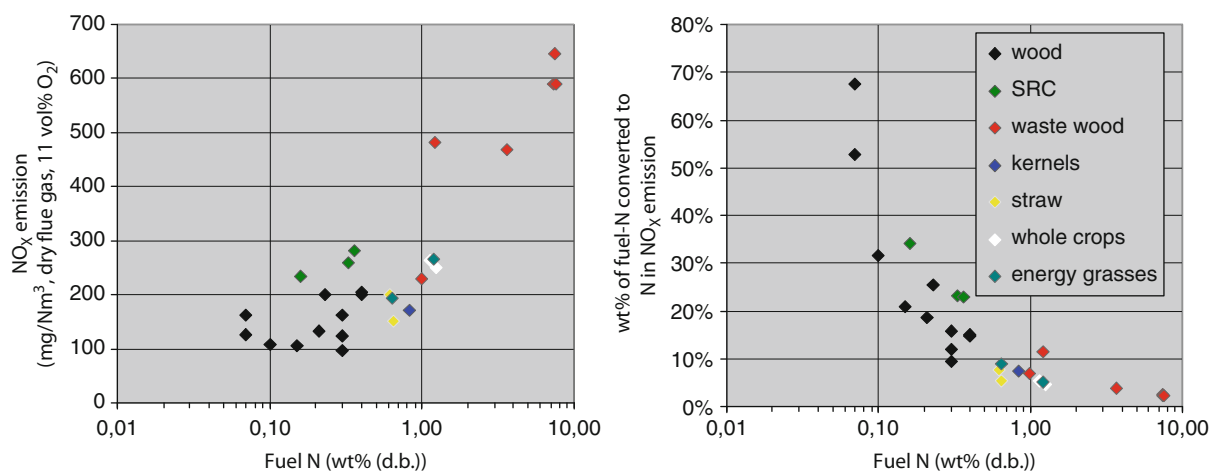
In order to reduce NO_x emissions from biomass combustion, several primary and secondary measures exist. For the utilization of chemically untreated biomass fuels, secondary measures are usually not necessary [12, 38]. If secondary measures are needed, they should always be combined with primary measures in order to efficiently utilize the NO_x reduction potential available and to reduce operating costs (additive utilization).

Air staging is a widely applied primary measure for NO_x reduction. Here primary and secondary combustion air is injected in separated zones. In order to efficiently reduce NO_x emissions, the air ratio in the primary combustion chamber should be between 0.6 and 0.9 and the residence time of the flue gas in the primary combustion chamber approx. 0.2–0.5 s at temperatures above 800°C. Furthermore, good mixing in the primary combustion zone is of great relevance. This can be achieved by appropriate flue gas recirculation. The potential for NO_x -reduction by air staging is between 30% and 60%.

A second possibility to reduce NO_x emissions by primary measures is fuel staging, where the primary and the secondary fuel is supplied in separate zones. Due to the complexity of the system, fuel staging is usually limited to large-scale applications. Approximately 70% primary fuel and 30% secondary fuel is used. The excess air ratio in the reduction zone following the secondary fuel supply should be between 0.6 and 0.8. Natural gas, biomass producer gas, shavings, or sawdust are usually utilized as secondary fuels. The potential of NO_x reduction by fuel staging amounts to 50–70%.

If primary measures fail to achieve the targeted NO_x reduction, they can be combined with secondary measures. These are selective noncatalytic reduction (SNCR) and selective catalytic reduction (SCR) [12, 39].

- In the SNCR process, ammonia or urea is injected into the flue gas at high temperatures and oxidizing conditions, usually between 850°C and 950°C and a residence time after injection of 0.3–0.5 s [39]. Because of the high temperature, this process does not need a catalyst to initiate the reactions. Ammonia is injected at a rate of between 1:1 and 2.2:1 mole ammonia to mole of NO_x reduced. About 60–70% NO reduction can be realized with



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 12

NO_x emissions (left) and fuel N converted to NO_x (right) in dependence of the N content in the fuel for different biomass fuels

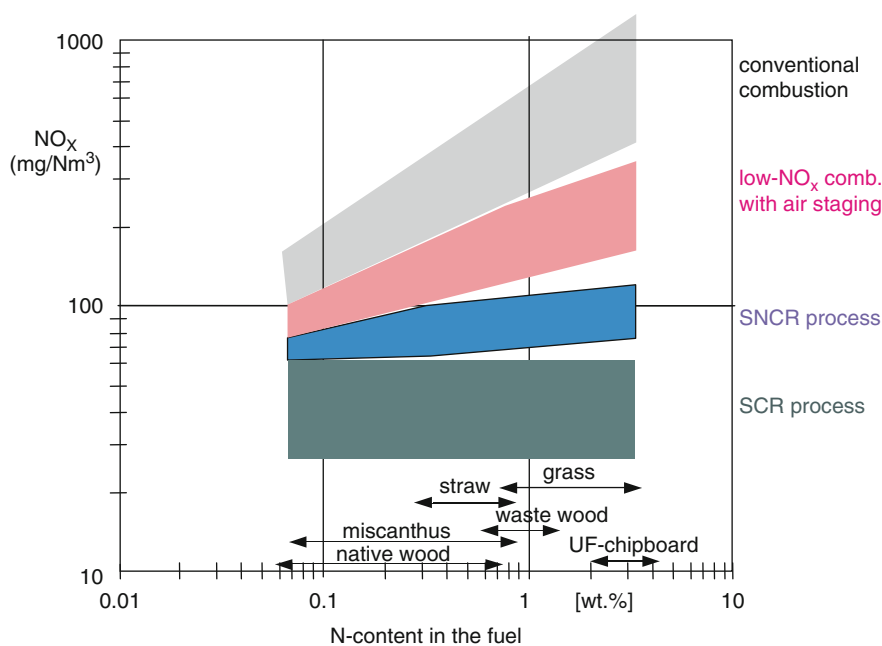
SNCR. This process requires an accurate temperature control to achieve optimum reduction conditions. If the temperature is too high, ammonia is oxidized to NO and if the temperature is too low, ammonia does not react at all and is emitted together with the NO_x. Additionally, a good mixing is very important. Most SNCR processes have an ammonia slip of some ppm in the flue gas leaving the stack.

- The SCR process reduces NO to N₂ by reactions with usually ammonia or urea in the presence of a platinum, titanium, or vanadium oxide catalyst. SCR operates optimally in a temperature range of 220–270°C using ammonia, and 400–450°C using urea [39]. The stoichiometric coefficient is usually around 1.0. Approximately an 80% NO_x reduction has been reported for SCR in fossil fuel combustion [40], where it is the most widely used secondary NO_x control technology. However, up to 95% NO_x reduction at 250°C without significant slippage of ammonia in a wood-firing system has been reported [39]. For the SCR process in combination with biomass combustion, the long-term behavior

of the catalyst can be a problem, as deactivation is likely. In this respect, an efficient dust precipitation stage upstream the SCR unit is an important requirement. SCR systems are considerably more expensive than SNCR systems but can be economically interesting for large-scale applications due to the better conversion efficiency achievable.

Figure 13 shows the relation between fuel N content, NO_x emission reduction measures, and NO_x emissions.

The Cl and S content in different biomass fuels vary in a wide range (Fig. 2) and consequently Cl- and S-related problems may vary considerably for different fuels. In biomass combustion systems usually 40–80 wt% (for wood chips and bark furnaces) and 80–85 wt% (for straw and cereal furnaces equipped with fibrous filters) are embedded in the ashes (related to the total amount of Cl in the biomass fuel). For S the respective values are 40–90 wt% (for wood chips and bark furnaces) and 45–55 wt% (for straw and cereal furnaces equipped with fibrous filters). The remaining Cl and S is emitted as HCl and SO₂



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 13

Relation between fuel N content, NO_x emission reduction measures, and NO_x emissions. (Explanations: NO_x calculated as NO₂ and related to dry flue gas and 11 vol% O₂)

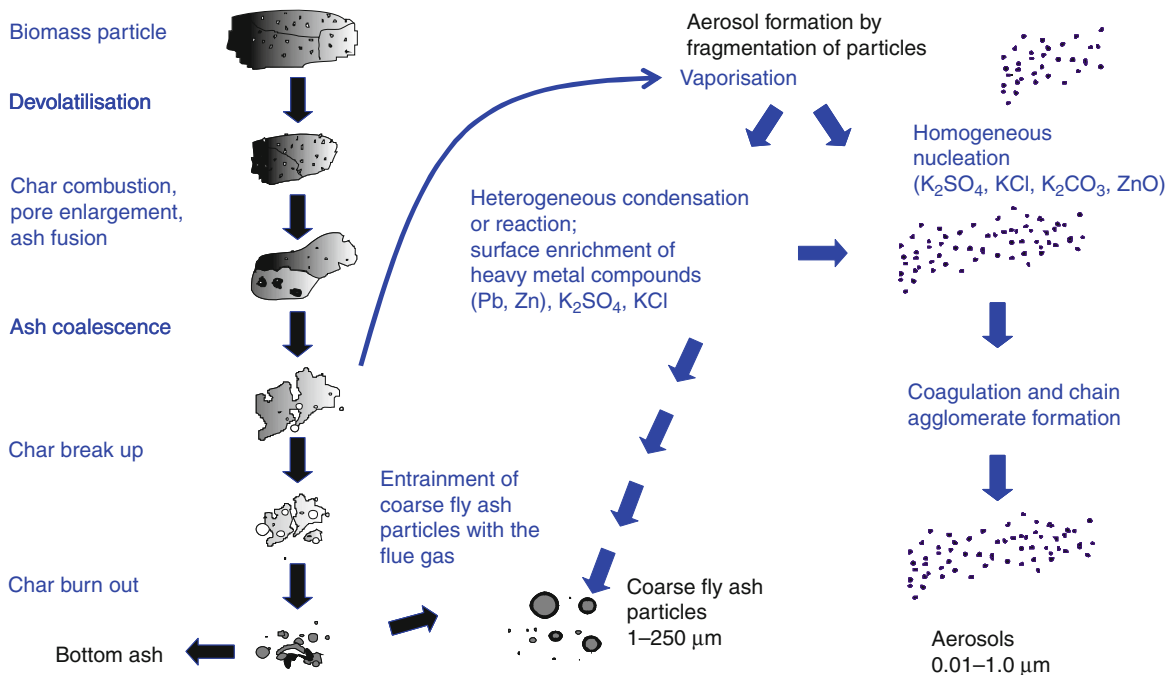
(and to a small extent as SO_3). Especially SO_3 emissions may cause corrosion problems in economizers since SO_3 increases the dew point of the flue gas considerably. If high HCl and/or SO_x emissions occur (e.g., for waste wood and straw combustion), the conventional approach to the control of HCl and SO_x emission reduction is the application of dry sorption with calcium hydroxide or sodium bicarbonate in combination with a baghouse filter.

Ash and Aerosol Formation

During the combustion of solid biofuels, the behavior of ash-forming elements follows a general scheme (Fig. 14). Below, a brief description of the basic principles of ash formation during biomass combustion is given.

Upon entering the combustion unit, the fuel is first dried, followed by devolatilization of the volatile organic matter. Subsequently, the remaining fixed carbon is oxidized during heterogeneous gas–solid reactions, which is called charcoal combustion. During these steps, the ash-forming elements behave in two different ways

depending on their volatility. Nonvolatile compounds such as Si, Ca, Mg, Fe, and Al are engaged in ash fusion as well as coagulation processes. Once the organic matter has been released or oxidized, these elements remain as coarse ash structures. Semi-volatile species such as K and Na and volatile species such as S, Cl, Zn, and Pb generally behave differently. A certain proportion up to the almost whole amount contained in the fuel of these elements is released to the gas phase due to the high temperatures occurring during combustion. There they undergo homogeneous gas phase reactions and later, due to supersaturation in the gas phase, these ash-forming vapors start to nucleate (formation of submicron aerosol particles) or condense on, respectively, react with the surfaces of existing particles or directly condense on heat exchanger surfaces. The submicron particles, so-called aerosols, form one important fraction of the fly ashes. The second fly ash fraction consists of small coarse ash particles entrained from the fuel bed with the flue gas. Depending on particle size, they are either precipitated from the flue gas in the furnace or boiler mainly by inertial impaction or gravitational settling, or are



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 14
Ash formation during biomass combustion

entrained with the flue gas, forming coarse fly ash emissions. Consequently, the most relevant difference between coarse fly ashes and aerosols is that coarse fly ashes always remain in the solid phase while aerosols undergo phase changes during their formation process (release to the gas phase and gas-to-particle conversion).

A share of the volatile ash-forming elements is not released to the gas phase but undergoes secondary reactions with the nonvolatile species (e.g., Ca, Si), thus being embedded in the coarse ash. The mechanisms of these secondary reactions and the parameters influencing the release of volatile species from the fuel are of great relevance for aerosol and deposit formation [41].

Especially with respect to the utilization of herbaceous biofuels as well as residues from agricultural, food, and biofuel industry, the special role of P has to be mentioned. In conventional wood fuels P is mainly inorganically bound and therefore, almost all P is embedded in the coarse ash fraction. In agricultural biomass as well as biogenic residues from industrial processes a share of the P may also be organically bound. Parts of this organically bound P can also be released to the gas phase and therefore participate in aerosol and deposit formation processes [11, 42].

The bottom ash represents the ash fraction remaining in the furnace after combustion of the fuel and is then removed by the de-ashing system. Coarse fly ash particles, which are entrained from the fuel bed with the flue gas, are partly precipitated on their way through the furnace and the boiler by inertial impaction, gravitational and centrifugal forces and therefore form the so-called furnace or boiler ash. Particles that are small enough to follow the flue gas on its way through the furnace and the boiler finally form the coarse fly ash emission at boiler outlet. The major share of these particles is precipitated in cyclones or filters and forms the cyclone fly ash and parts of the filter fly ash.

Table 6 gives typical data concerning the fractionation of ashes into bottom ashes, cyclone fly ashes and filter fly ashes in modern fixed-bed biomass combustion plants [12]. On the contrary, in fluidized bed and pulverized fuel combustion the amount of bottom ash is low while the fly ash fractions clearly dominate. It is recommended to use a two-stage fly ash precipitation (cyclone plus filter) in order to increase the overall dust precipitation efficiency.

Aerosols are formed by gas-to-particle conversion processes in the furnace and in the boiler. Some of the aerosol particles coagulate with coarse fly ashes due to collisions. Moreover, a smaller part of aerosols is also precipitated in the boiler and therefore contributes to the boiler ash while the major part of this fraction is emitted with the flue gas at boiler outlet. Since aerosols are characterized by particle sizes significantly below 1 μm (ae.d.), precipitation in a cyclone, which usually has a cut diameter of about 5–10 μm , is almost impossible. Thus, aerosols can only be precipitated in more advanced filter systems such as baghouse filters and electrostatic precipitators (ESP). Consequently, aerosols do not contribute to the cyclone fly ashes but to the filter fly ashes as well as to the particulate emissions at filter outlet.

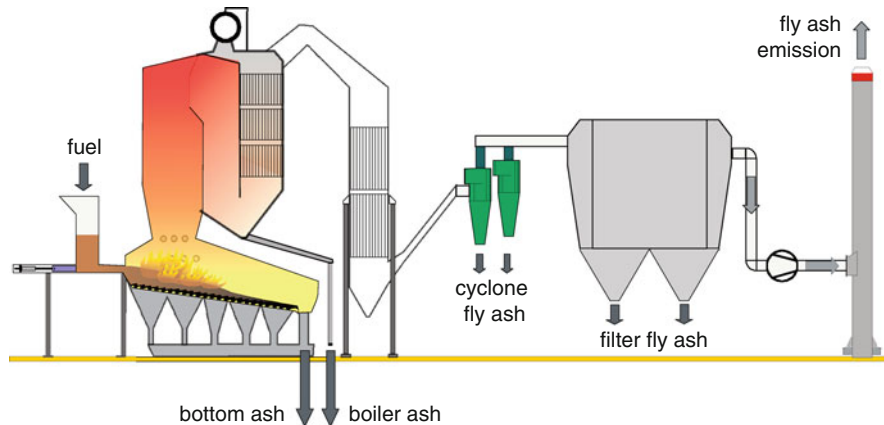
Figure 15 gives the scheme of a typical large-scale grate-fired steam boiler to show where the different ash fractions occur.

The initial step for coarse fly ash formation is the entrainment of small ash, fuel and charcoal particles from the fuel bed with the flue gas. The mass of particles entrained from the fuel bed is influenced by the following parameters:

- The fuel, the ash content and the particle size of the fuel are of major relevance for particle entrainment. The probability that an ash particle is entrained from the fuel bed with the flue gas significantly increases with increasing ash content of the fuel

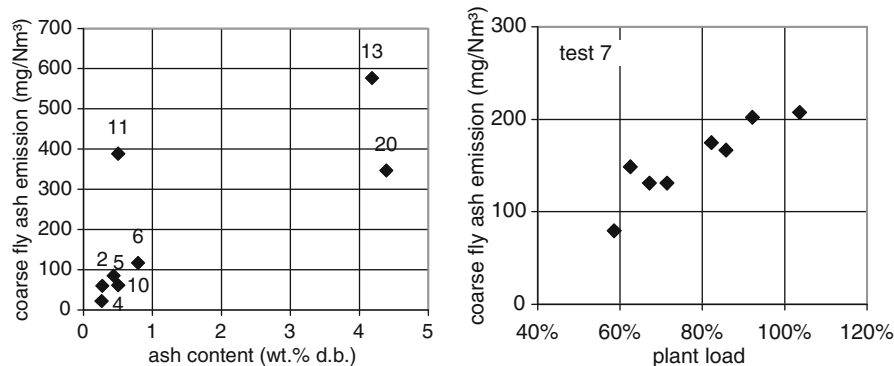
Biomass Energy Heat Provision in Modern Large-Scale Systems. Table 6 Typical shares of the different ash fractions on the total ashes produced

	Bark combustion	Wood chips combustion	Sawdust combustion	Straw combustion
Bottom ash	65–85	60–90	20–30	80–90
Cyclone fly ash	10–25	10–30	50–70	2–5
Filter fly ash	2–10	2–10	10–25	5–15



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 15

Ash fractions in a biomass combustion unit. (Explanations: typical plant scheme of a large-scale grate-fired steam boiler)



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 16

Influence of the ash content of the fuel (*left picture*) and the boiler load (*right picture*) on the total fly ash emissions.

(Explanations: emission data related to dry flue gas and 13 vol% O₂, d.b. dry basis, results from tests performed at different grate fired systems, for the results presented on the left picture only measurements at full load (>80% of the nominal boiler capacity) were considered)

(Fig. 16, left). Particle entrainment also increases with decreasing particle size of the fuel.

- The boiler load also influences particle entrainment from the fuel bed. Measurements performed show a clear tendency of increasing fly ash emissions with increasing boiler load of the combustion plant (Fig. 16, right).
- In the case of grate-fired systems, the grate system applied as well as the design of the grate have an influence on ash entrainment. Grate systems such as horizontally moving grates, which keep the fuel bed comparably undisturbed during its movement

along the grate, show a tendency toward lower ash entrainment than grate systems such as inclined moving grates (due to gravity enforced movements) and vibrating grates. Moreover, the grate design should avoid locally excessive combustion air velocities in the fuel bed, which could lead to channeling and increased fuel and ash entrainment.

- The control system of the combustion plant should be designed in order to achieve a smooth fuel transport on the grate and to minimize disturbances of the fuel bed, which lead to increased particle entrainment.

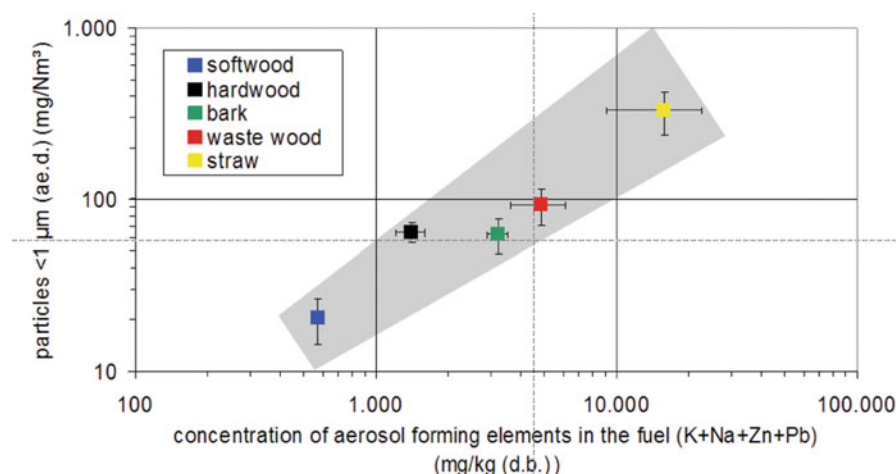
A considerable number of tests have been carried out to investigate possible parameters influencing the mass of aerosols formed during combustion. Therefore, the combustion air ratio, the furnaces temperature, the moisture content of the fuel, as well as the influence of flue gas recirculation are considered. These parameters are varied during test runs in a range, which is typical for the operation of fixed-bed combustion units. Based on this no significant influences of the parameters mentioned on the mass of aerosols formed during combustion could be identified. This leads to the conclusion that as long as almost complete burnout prevails, the fuel composition, or in more detail, the release of aerosol-forming species from the fuel during combustion, is the most relevant parameter determining the mass of aerosols formed. This statement is confirmed by the data presented in Fig. 17, where the concentrations of the most relevant aerosol-forming elements K, Na, Zn, and Pb in the fuel are plotted against the average aerosol emissions measured at boiler outlet of medium and large-scale fixed-bed combustion plants [43].

Results from test runs including element balances over fixed-bed combustion plants performed with beech, bark, and waste wood have shown that usually 10–40 wt% of K and Na, more than 80% of S, more

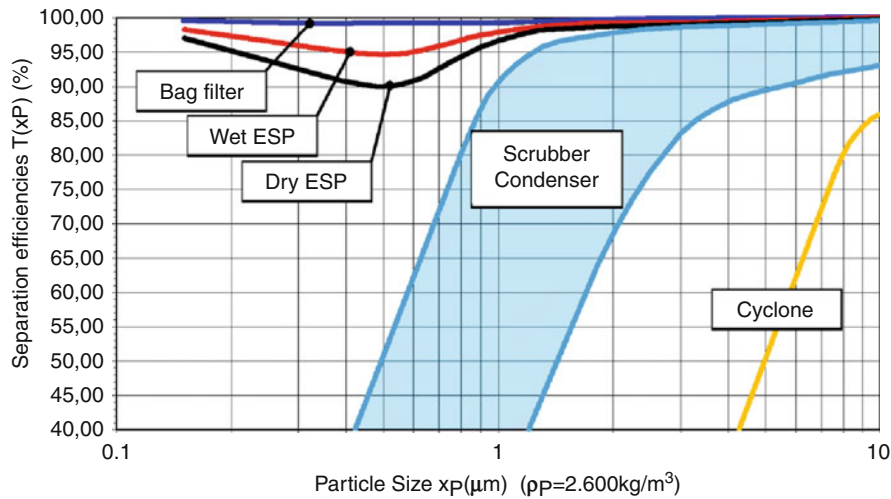
than 95% of Cl, as well as more than 80% of Zn and Pb are released to the gas phase.

Different particle precipitation technologies are available in order to reduce particle emissions from biomass combustion plants. However, not every technology suits every need. Among the determining factors are the particle size, required collection efficiency, gas flow, allowed time between cleanings, the detailed nature of the particles, and the presence of tars in the flue gas. The following rules of thumb may be helpful in selecting particle control technologies for biomass combustion applications:

- Sticky particles (e.g., tars) must be collected in a liquid (e.g., with a scrubber). Alternatively, a bag filter or an electrostatic filter with coated collecting surfaces is possible. There must also be a way to process the produced contaminated liquids.
- Particles that adhere well to each other but not to solid surfaces are easy to collect. Those that do the reverse often need special surfaces, e.g., Teflon-coated fibers in filters that release collected particles well during cleaning.
- The electrical properties of the particles are of paramount importance in electrostatic filters, and they are often significant in other control devices where friction-induced electrostatic charges on the particles can aid or hinder collection.



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 17
Influence of the fuel used on the mass of aerosols formed



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 18

Collection efficiencies for different particle control technologies [44]

- For nonsticky particles larger than about 5 μm , a cyclone separator is probably the only device to consider.
- For particles much smaller than 5 μm normally electrostatic filters, baghouse filters or scrubbers are considered. Each of these can collect particles as small as a fraction of a micron.
- For large flows, the pumping cost makes scrubbers very expensive; other devices are preferable.
- Corrosion resistance and dew point must always be considered.

Figure 18 shows the collection efficiencies for some proven particle precipitation technologies as a function of particle diameter. Table 7 summarizes typical sizes of particles removed by several proven particle control technologies and typical removal efficiencies.

Below, the most important particle precipitation technologies for biomass combustion plants are briefly discussed.

- *Cyclones.* Particle separation within a cyclone is based on the principle of gravity in combination with centrifugal forces. Gas and solid particles are exposed to centrifugal forces. Because of the centrifugal forces, particles hit the wall and slide down into a container.
- *Multicyclones.* The separation efficiency of a cyclone can be improved by increasing the centrifugal force

Biomass Energy Heat Provision in Modern Large-Scale Systems. Table 7 Typical sizes of particles removed by various particle control technologies

Particle control technology	Particle size (μm)	Efficiency (%)
Settling chambers	>50	<50
Cyclones	>5	<80
Multicyclones	>5	<90
Electrostatic filters	<1	>99
Bag filters	<1	>99
Spray chambers	>10	<80
Impingement scrubbers	>3	<80
Cyclone spray chambers	>3	<80
Venturi scrubbers	>0.5	<99

through reduction of the cyclone diameter. In order to prevent loss of capacity, several cyclones can be used in parallel.

- *Electrostatic precipitators.* In an electrostatic precipitator, the particles are first electrically charged. Then they are exposed to an electrical field in which they are attracted to an electrode. In practice, separation can be done in one or two

stages. In case of two-stage separation, charging of the particles is first done in a very strong electric field, after which a relatively weak field separates the particles.

- **Baghouse filters.** The construction of a bag filter consists of a filter or cloth, tightly woven from special fibers and hung up in a closed construction through which flue gas passes. The separation efficiency of bag filters is quite high, even with high flue gas flow rates and high particle content. The first layer of particles improves the filtration efficiency. However, as more particles settle on the cloth, the pressure drop increases. Therefore, periodically the cloth is cleaned by vibration or pressurized air. Cloth filters are usually manufactured in cylindrical shapes.
- **Scrubbers.** In scrubbers, particles are scrubbed out from the flue gas by water droplets of various sizes, depending on the type of scrubber used. The particles are removed by collision and interception between droplets and particles. Upon impact, the particles are wetted and carried by the water droplet. The more droplets are formed, the more efficient the unit is. Therefore, the droplets must be small. Smaller-diameter spray nozzles will produce smaller droplets but will also result in higher pressure drops, consuming more energy. Since efficiency increases as the droplet size decreases, efficiency increases with increasing pressure drop.

Slagging, Deposit Formation, and Corrosion

Ash melting, deposit formation, and corrosion are the major internal plant operation-related problems associated to ash-forming elements. Ash melting can occur on the grate and on non-cooled furnace walls. Moreover, fly ash depositions formed on heat exchanger surfaces can also melt. As soon as ashes start partly to melt or fuse, the resulting ash pieces usually called slag.

Deposit formation means the formation of ash layers on furnace and boiler surfaces (furnace walls, radiative and convective heat exchanger surfaces). Thereby it is often distinguished between slagging and fouling. Slagging is the formation of molten or partially fused deposits on furnace walls or convection surfaces exposed to radiant heat. Fouling is commonly defined

as the formation of deposits on convective heat exchanger surfaces such as boiler tubes in hot water fire tube boilers and superheaters in water tube steam boilers.

Ash Melting and Slagging Ash melting on the grate can result in problems with the combustion process since slag plates can hinder the primary airflow through the fuel bed. Moreover, larger slag pieces can lead to damages of the grate as well as to problems with blocking the de-ashing system. Slagging and deposit formation in the furnace can lead to increased pressure losses due to smaller flow areas in narrow parts of the furnace, and slagging and deposit formation in the radiative sections of steam boilers can lead to reduced heat transfer. Figure 19 shows typical examples for slagging on a grate and for slag formation in the radiative part of a steam boiler.

Slag formation in biomass furnaces and boilers is always a result of ash melting. Not necessarily, the whole ash has to melt. Usually, single phases which show low melting temperatures start to melt and act as glue between ash particles with higher melting temperatures. Therefore, always different phases of molten and non-molten compounds can be found when analyzing slag pieces or hard deposits. The formation of slag pieces and hard deposits starts at temperatures where about 15 wt% of the ash in a certain ash piece are molten (T_{15}) [45]. At the temperature where the share of molten phases exceeds 70 wt% (T_{70}), the slag/deposit typically starts to flow.

Thermodynamic equilibrium calculations have turned out to be a useful tool to evaluate the melting behavior of biomass ashes. Thereby, thermodynamic equilibrium calculations of multiphase and multicomponent systems simultaneously handling hundreds of chemical species are applied. For combustion systems, both major and minor ash-forming components are taken into account. The reactions of the minor components are usually dependent on the reactions of the major components. However, minor elements (especially Pb and Zn as well as Cl) are also of great relevance, since they usually contribute to a reduction of the ash melting temperatures of ash mixtures. The thermodynamic databases used must be of high quality because small errors and deviations in data for main components give bigger errors on

small components and give wrong results. Especially concerning systems containing P only restricted thermodynamic data are presently available.

One big advantage of thermodynamic equilibrium calculations is that they can be performed for typical grate ash as well as fly ash compositions separately. Therefore, also the significantly differing chemical composition of these fractions can be taken into account when determining their melting behavior

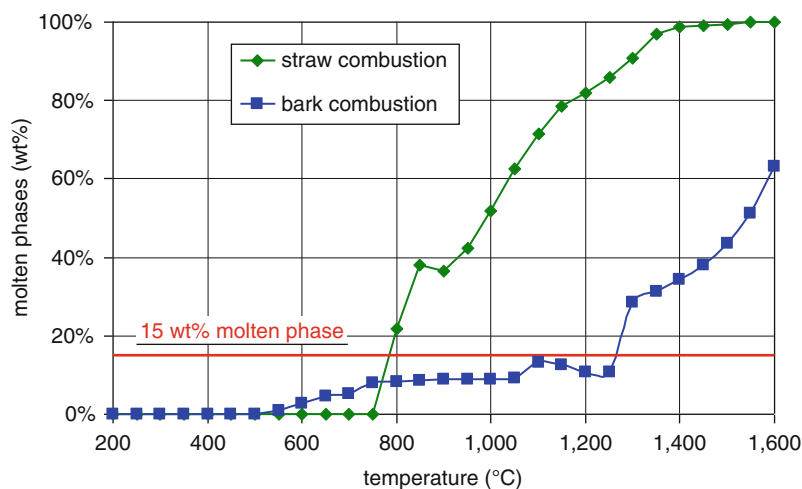
(e.g., fly ashes with high amounts of alkaline metal salts show typically considerably lower melting temperatures).

Figure 20 presents results from thermodynamic equilibrium calculations performed for bottom ashes from bark and straw combustion. Here the amount of molten phase in the ash is plotted against the temperature. Since the input data for the calculations have been taken from bottom ash analyses performed during



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 19

Examples for slag formation. (Explanations: *left* slag formation in a moving grate furnace during combustion of industrial biogenic residues, *right* slag formation in the radiative section of a steam boiler)



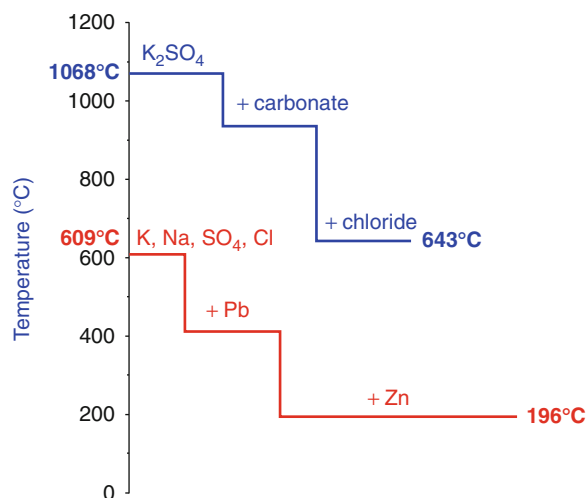
Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 20

Formation of molten phases in bottom ashes from bark and straw combustion – results from thermodynamic equilibrium calculations [47]

real-scale test runs, realistic ash compositions form the basis for these calculations. In the case of straw combustion a rapid increase of the molten phases at temperatures above 750°C occurs. T_{15} is reached below 800°C. For ashes from bark combustion this effect happens at significantly higher temperatures of about 1,250°C. Moreover, the results of the calculations provide data about the compositions of the molten phases as well as the changes of the compositions depending on temperature.

These results can then also be compared with results from SEM/EDX analyses of molten phases of ash and slag pieces in order to get a more detailed picture of the ash-melting behavior of complex ash mixtures. Such calculations can be useful to indicate relevant trends and differences between various fuels and ash fractions.

Figure 21 shows the influence of heavy metals on the melting behavior of Cl-containing fly ash mixtures. The upper part of the blue line for instance shows the ash melting point of pure K_2SO_4 (melting point: 1,068°C), which is a relevant compound of aerosols formed during biomass combustion. If K-carbonate is formed the first melting point decreases to 940°C, and



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 21

The influence of different K salts as well as of heavy metals on the melting temperatures of ash mixtures.

(Explanations: Source [41])

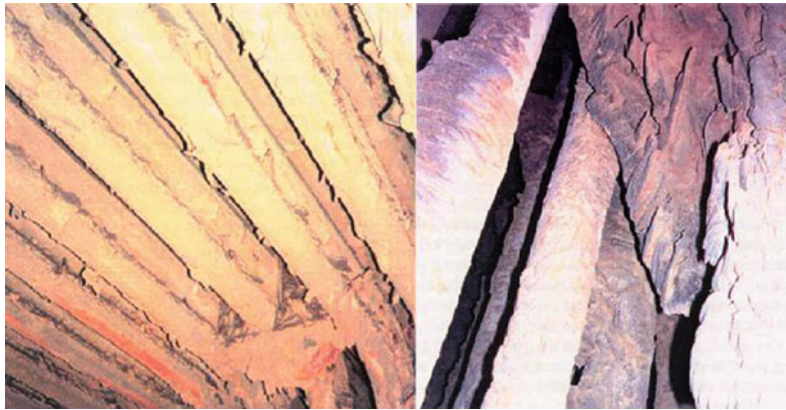
if K-chloride is formed to 643°C. Small amounts of Na (red curve) decrease the first melting point to 609°C. The presence of Pb and Zn, even in small amounts compared to K and Na, results in molten phases at such low temperatures as 196°C.

As it can be revealed from Figs. 20 and 21, ashes from different biomass fuels can show significantly different ash melting behaviors and therefore, measures to reduce problems with ash melting and slagging in combustion plants have always to be adjusted to the chemical composition of the fuel applied. Appropriate measures usually implemented in modern biomass combustion systems are grate cooling, furnace cooling by cooled walls or flue gas recirculation, the appropriate adjustment of the flue gas inlet temperature in convective boiler sections and of the superheater steam temperature, as well as the utilization of additives.

Deposit Formation Deposits are formed by coarse fly ashes as well as condensable gaseous ash-forming compounds present in the flue gas. Under the typical conditions prevailing in biomass hot water, thermal oil, and steam boilers, the direct condensation of ash-forming vapors on heat exchanger surfaces and inertial impaction are of major relevance concerning deposit formation. Thermophoresis has certain relevance, especially when high-temperature gradients between a cooled wall and the flue gas occur. Other mechanisms such as turbulent eddy impaction, Brownian diffusion, and diffusiophoresis are of minor relevance.

With increasing deposit thickness, the heat transfer through the heat exchanger tubes decreases which results in a loss of efficiency. Severe deposit formation (fouling) can block the flue gas pathways through heat exchanger sections. Figure 22 shows deposits on superheater tubes of a waste wood fired steam boiler.

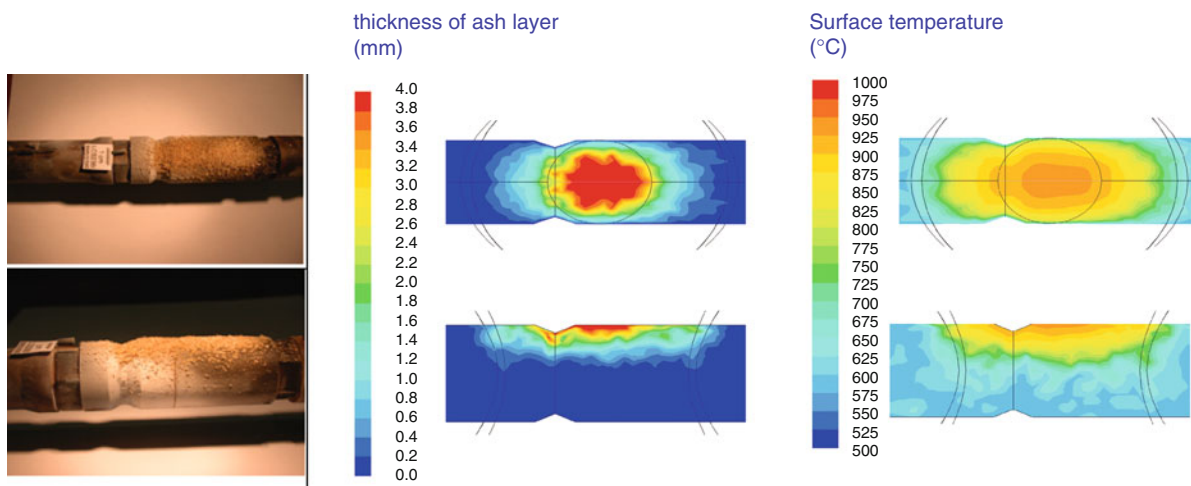
The temperature at the gas side deposit surface increases with increasing deposit thickness (Fig. 23). There, results gained from CFD simulations performed for a superheater tube with a surface temperature of 590°C exposed to a flue gas stream with 1,050°C are presented. From the simulation results, it can be derived that with increasing deposit thickness the surface temperature at the flue gas side significantly increases and finally reaches more than 900°C at



B

Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 22

Pictures of deposits formed on superheater tubes of a steam boiler during waste wood combustion. (Explanations: *left* typical deposit formation, *right* severe deposit formation leading to the blocking of heat exchanger pathways)



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 23

Ash deposit layer on a water-cooled deposition probe (*left*) compared with CFD simulations performed (*middle*) and influence of ash depositions on the surface temperatures (*right*). (Explanations: bulk flue gas temperature 1,050°C, clean probe surface temperature 590°C, figures at the top *top view* figures at the bottom *side view*)

a deposit thickness of about 4 mm. With increasing surface temperature the fraction of molten phases increases and therefore the deposit becomes more sticky and grows faster. Finally, higher amounts of molten phases also lead to the formation of hard deposit layers problematic to be removed.

Consequently, it is important to periodically clean heat exchanger surfaces in order to reduce deposit

growth. Therefore, different automatic heat exchanger cleaning systems listed below are usually applied.

- Fire tube boilers can be cleaned by injecting pressurized air into the tubes. Thereby, in an interval of some hours for some milliseconds an air pulse is injected which cleans the boiler tubes. Membrane valves control this air pulse. To protect these valves

from too high temperatures, the cleaning system is usually installed on the wall of the turning chamber between the first and the second duct (cleaning of the first duct in countercurrent and of the second duct in cocurrent flow).

- In water tube steam boilers, usually soot blowers are installed to remove deposits from the superheater surfaces. If there is an increased risk for deposit formation on the tubes in the radiative boiler section, sometimes water canons are also installed. Moreover, shot cleaning by injecting small metal balls into the heat exchanger bundles is sometimes applied.

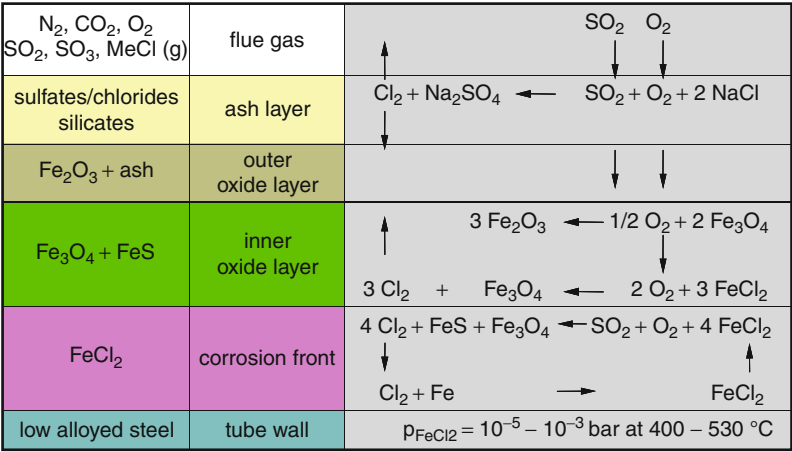
Besides these secondary measures also primary measures for the reduction of deposit formation should be considered. These measures involve the adjustment of the flue gas and tube surface temperatures to the expected properties of condensing ash-forming compounds (which depend on the composition of the fuel applied) during boiler design as well as a careful control of the flue gas temperatures during operation. Moreover, additives can be used to reduce deposit formation.

Additionally, load changes can lead to changing flue gas and boiler tube temperatures. Due to thermal stresses, deposits can be partly destroyed during phases with load changes. This effect can additionally support the efficiency of automatic cleaning systems.

Corrosion Corrosion is an important issue especially for biomass plants utilizing fuels with high chlorine and sulfur contents. For biomass combustion, three possible corrosion mechanisms are distinguished:

- Active oxidation
- Corrosion due to molten alkaline metal compounds and other salts
- Acid dew point corrosion

The so-called active oxidation (or high-temperature chlorine corrosion) is the most relevant corrosion mechanism in biomass boilers (see Fig. 24). This mechanism is based on the formation of Cl-containing deposit layers on the boiler tube surfaces. The first step of deposit formation is the formation of an ash layer by direct condensation of alkaline metal and heavy metal salts (chlorides and sulfates) on the boiler tube surfaces. The chemical composition of this condensed layer depends on the tube surface temperature and on the fuel composition, respectively, the release behavior of alkaline metals, Cl, S and easily volatile heavy metals from the fuel to the gas phase. If the molar ratio 2S/Cl released from the fuel to the gas phase is high and flue gas temperatures above 850°C occur, mainly alkaline metal sulfate vapors are formed while, if this ratio is low, the formation of alkaline metal chlorides usually dominates.



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 24
Schematic explanation of the active oxidation mechanism [49]

Combustion tests with chemically untreated wood fuels as well as waste wood have shown, that, when utilizing chemically untreated biomass, at tube surface temperatures above 500°C the Cl-concentration in the deposits starts to significantly decrease [46]. As soon as the surface temperature exceeds 550°C almost no Cl could be found in the deposits. Superheaters of modern steam boilers utilizing chemically untreated biofuels are usually designed for steam temperatures between 480°C and 540°C and thus operate in this temperature range.

In hot water boilers on the other hand, where the tube surface temperatures are rather low (around 100°C) compared with steam boilers, Cl containing deposits are found even when utilizing fuels with very low Cl contents and high 2S/Cl ratios.

To start the process of active oxidation besides Cl-containing deposits also gaseous SO_2 is needed. SO_2 reacts with alkaline metal chlorides under formation of alkali metal sulfate and release of Cl_2 . This process happens in the deposit layer and therefore, Cl_2 diffusing toward the inner oxide layer can form FeCl_2 . FeCl_2 has, depending on the temperature, a certain volatility under reducing conditions and can therefore be vaporized. The vapor formed diffuses from the tube wall into the ash layer. There, it is oxidized again (due to the increasing partial pressure of O_2 toward the flue gas) and the Cl_2 , which is released, can diffuse back to the tube wall and react there again with iron oxide. Following this process, even small amounts of Cl released in the ash layer have the potential to cause considerable corrosion damages if the residence time of the ash layer on the tube surfaces is high enough.

Three measures to reduce active oxidation can be mentioned:

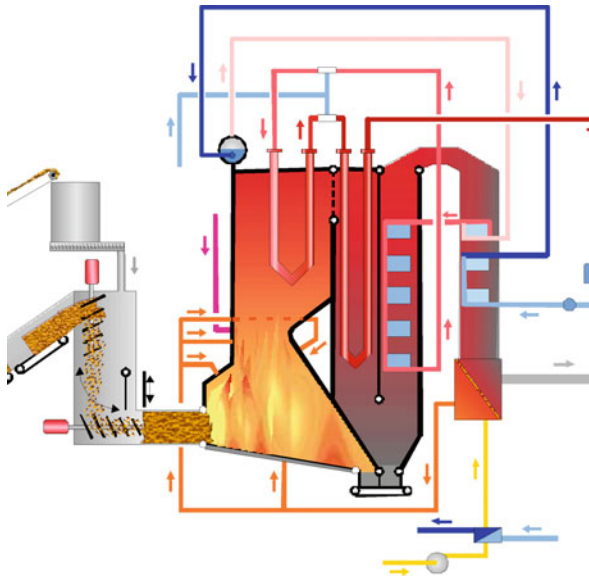
1. Utilization of fuels with a high molar 2S/Cl ratio to enforce the formation of K_2SO_4 instead of KCl layers.
2. Lower tube surface temperatures considerably reduce the evaporation of FeCl_2 and thus slow down the corrosion process.
3. Frequent cleaning of the boiler tubes (implementation of automatic boiler cleaning systems) in order to keep the residence time of ash layers on the tube surfaces low and thus to limit the sulfation reactions.

The second corrosion mechanism depends on the presence of alkaline metal and heavy metal

chlorides and sulfates on boiler tube surfaces. These chlorides and sulfates and especially mixtures of them can show comparably low melting temperatures (Fig. 21). Molten salt phases thereby can attack the tube material. This mechanism is of minor relevance for the combustion of chemically untreated fuels. However, in the case of the combustion of waste material such as waste wood, which contains comparably high heavy metal concentrations, it can be of relevance.

During the utilization of chemically untreated woody fuels, usually no problems with acid dew point-induced corrosion are observed. However, when utilizing waste wood or biogeneous residues, this mechanism can become important. If a fuel contains high S concentrations and comparably low K and Ca concentrations, a relevant amount of S will not be embedded into the ashes by the formation of K_2SO_4 and CaSO_4 but remains as SO_2 in the gaseous phase. A part of the SO_2 reacts to SO_3 and then with water (flue gas moisture) to form H_2SO_4 . The acid dew point temperature (ADT) of H_2SO_4 significantly increases with increasing SO_3 -concentrations in the flue gas. If the temperatures of boiler or economizer tube surfaces are below this dew point temperature, H_2SO_4 condensation followed by corrosion takes place. Therefore, an appropriate adjustment of the surface temperatures of economizers and hot water boilers beyond the expected acid dew points is of relevance.

For future technological developments, the main aim is to increase the thermal and electric efficiency by increasing the steam parameters. Thereby, especially fouling and corrosion-related problems have to be considered. For straw combustion for instance, a steam temperature of 542°C leading to an electric efficiency of 31.7% has already been achieved, e.g., in the CHP plant Maribo-Sakskøbing (Denmark). Figure 25 shows a scheme of this CHP plant utilizing wheat straw. Here appropriate technological solutions in order to reduce corrosion particularly in the high-temperature stages of the superheaters have been implemented. The boiler and in particular the superheaters are specially designed to handle the harsh condition from combustion of straw and straw-like biomass fuels in a highly efficient boiler with advanced steam data. The first and second pass superheater stages are operated in the so-called slagging mode.



Biomass Energy Heat Provision in Modern Large-Scale Systems. Figure 25

Case study for appropriate technological solutions in order to reduce corrosion-related problems – the CHP plant Maribo-Sakskøbing (Denmark). (Explanations: Source: Bioener ApS; main fuel wheat straw, steam pressure 92 bar, steam temperature 542°C, power output (gross) 10.6 MW, thermal output 20 MW, electric efficiency (gross) 31.7%, thermal plant efficiency 60%, total plant efficiency 91.7%, efficiencies related to fuel power input (NCV))

A continuous K_2SO_4 slag layer on tube surfaces protects the superheater material against high-temperature chlorine corrosion. The slag layer is several cm thick and only removed when the plant is shut down due to thermal stress. By this way, electric efficiencies of more than 31% can be achieved in medium-scale CHP plants at plant availabilities of above 90%.

For CHP plants utilizing wood fuels, even higher steam parameters and consequently efficiencies should be the target for future developments. First R&D results show low corrosion potentials due to decreasing Cl-concentrations in deposits at temperatures above 540°C. However, further long-term tests are needed. For such tests newly developed corrosion probes are a useful development tool [48, 49]. The correct choice of the superheater materials plays an important role for such advanced approaches. Moreover, the

application of additives which reduce the Cl-content of deposits can contribute to a further increase of the steam temperatures.

Intelligent Process Control Systems

State-of-the-art control systems for biomass combustion plants usually work with four control circuits which control the load, the furnace temperatures, the pressure in the furnace, and the secondary air ratio. Each of these control circuits is responsible to set respective output parameters based on measured data and defined setpoints. They are to a large extent independent from each other. Dependencies and sometimes highly nonlinear interrelations between the different output parameters are not or only to a small extent taken into consideration. Consequently, conventional control systems work sufficiently efficient at steady state but not efficient in intermediate conditions (e.g., load changes or changes of the fuel quality). The potential of a modern biomass furnace with an optimized furnace geometry and nozzle design is not fully utilized concerning low emission operation and high energetic efficiencies by conventional control systems.

Within recent years control systems implementing neuronal networks, fuzzy logic, and model-based control gained more and more importance but are at the moment not or only to a small extent applied for biomass combustion plants.

With neuronal networks, it is possible to develop a mathematical model in a fast and convenient way directly from experimental data. The major drawback is that the models are not based on the underlying physical relations and are only valid within the scope of the experimental data provided. Consequently, validity is not guaranteed for every state.

Fuzzy control is based on a description of a system based on fuzzy logic, which allows to deduce a mathematical model from a linguistical description of the system behavior. Hence, fuzzy control has the advantage that the operator's expertise can be used to develop a control strategy very quickly. The disadvantage of fuzzy concepts is the fact that states not considered by rules can lead to malfunctions and that there is no deterministic procedure for the design of a fuzzy controller. Consequently, liberties in the realization of

fuzzy controllers can degrade the results significantly. Up to now, fuzzy concepts are partly implemented in control systems for biomass combustion plants but there is no control system available completely based on fuzzy logic.

Model-based concepts require a preferably simple mathematical model that describes the main interrelations of the physical system to be controlled [50–53]. Based on this mathematical model, it is possible to develop a controller taking the nonlinearity and the coupling of the different process variables explicitly into account, wherefore a well-established theory is available. Consequently, the so designed model-based controller is able to react more efficiently on unsteady operating conditions than the currently in combustion plants used control systems. The only disadvantage of the described model based control strategies is that they are very labor intensive in the case that no applicable mathematical model is available. If such models are available, then model based systems are evaluated to be the most suitable and efficient solution.

New control concepts (especially model based control strategies and fuzzy control) will gain more importance for biomass combustion systems in the near future.

Future Directions

Biomass is the most important renewable energy source in the European Union. In the field of energetic utilization of solid biomass, combustion is the most advanced and market-proven application. Consequently, the energetic use of solid biomass is primarily based on biomass combustion at present. Biomass combustion technologies, like fixed bed, fluidized bed, and pulverized fuel combustion, are currently available for different types of biomass fuels covering a wide range of plant capacities. Concerning plant size, the different applications of biomass combustion can be divided into small-scale biomass combustion systems (capacity range below 100 kW_{th}), medium-scale combustion systems (capacity range between 0.1 and 20 MW_{th}), large-scale combustion systems (capacity range above 20 MW_{th}), and co-firing of biomass in coal-fired power stations (capacity range usually some 100 MW_{th}).

The necessary measures for a complete combustion are well known in principle. But they are still not implemented in all combustion plants operating today. Such improvement would comprise optimized mixing of gases in the furnace as well as implementation of updated and more advanced process control systems. The thermal conversion efficiency of existing combustion plants also has a potential for improvement. These improvement potentials are mainly in the way the plant is operated, like improved maintenance, correct adjustment of excess air ratio, and optimized management of heat distribution. Moreover, process economy for large-scale combustion of biomass fuels with high water contents can be significantly improved by using flue gas condensation.

Regarding plant design, chemical and physical properties of biomass fuels are of great importance. The fuel properties affect fuel transport, storage, and feeding systems as well as the combustion and boiler technology. Especially ash-related problems like aerosol formation, slagging, deposit formation, and corrosion in biomass combustion processes are always strongly associated with the fuel chemistry, in detail, with the concentration and speciation of inorganic compounds in the fuel. Important guiding parameters are, in this respect, the molar ratios $(K + Na)/(2S + Cl)$, $2S/Cl$, and the sum of K, Na, Zn, and Pb in the fuel. High molar ratios of $(K + Na)/(2S + Cl)$ indicate lower HCl and SO_x emissions. The molar ratio of $2S/Cl$ indicates the preferred formation of alkaline sulfates or alkaline chlorides. K, Na, Zn, and Pb are the most relevant aerosol-forming elements. With increasing concentrations of these elements, the probability of aerosol formation as well as deposit formation increase as well. Consequently, if an ash-related problem has to be evaluated always comprehensive knowledge about the fuel is needed.

Beside woody fuels, new feedstocks like annual and perennial energy crops, agricultural and industrial biogenic residues, as well as chemically treated biofuels such as urban waste wood and demolition wood, can significantly contribute to the future energy supply. These types of fuels typically contain higher amounts of nitrogen and volatile ash-forming elements (K, Na, Zn, and Pb) as well as corrosive elements (S and Cl) than the typically chemically untreated woody fuels mainly used today. For this reason, special combustion

and process control systems as well as new processes for efficient energy recovery and emission reduction will be required.

NO_x emissions from biomass combustion applications are mainly due to the oxidization of fuel-bound nitrogen, whereas NO_x formed from air-bound nitrogen is usually of minor relevance in most biomass combustion applications due to moderate combustion temperatures. Primary measures or combinations of primary and secondary measures can efficiently reduce NO_x emissions from biomass combustion. In addition, CFD-modeling of NO_x formation is of great relevance for an improved future plant design.

The reduction of dust and fine particle emissions especially by primary measures is of great relevance for small-scale applications typically not equipped with filter systems. For medium to large-scale plants, efficient filters like ESPs or baghouse filters are state of the art.

CHP technologies based on biomass combustion have reached a high level of development. For large-scale CHP plants (above 2,000 kW_{el}), the steam turbine process is economically and technically feasible. In the medium-scale power range (200–3,000 kW_{el}) the organic Rankine cycle (ORC) process has proven its technological maturity. For small-scale CHP plants (below 100 kW_{el}) the Stirling engine process and the micro gas turbine are in a demonstration phase. However, these technologies have not proven their technological maturity yet.

On going research mainly focuses on the utilization of new biomass fuels (annual crops, short rotation plants, waste materials from the agricultural and the food industry, etc) as well as the further development of combustion technology toward next generation (“zero emissions”) systems. The main focus regarding emission reduction is on aerosol emissions as well as on NO_x reduction (for all size ranges). Concerning CHP systems new developments focus on advanced and highly efficient systems. In this respect, increased steam parameters and higher availability are important targets. Regarding process control strategies for combustion plants, new concepts like model based systems will gain more and more importance. Future modeling activities aim at CFD models to simulate the whole biomass combustion plant (“virtual biomass

combustion plant”) interlinking solid fuel combustion, gas phase reactions, the boiler as well as emissions and ash-related problems.

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Biomass Energy Heat Provision in Modern Small-Scale Systems

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Article Outline

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Glossary

Annual efficiency Ratio of useful heat provided and total fuel energy input throughout a full heating season.

Boiler Central heating boilers are designed to avoid the loss of heat to the surrounding space. For this reason, they are equipped with water heat exchangers using hot water central heating circuit through which the transfer of heat to the relevant rooms is realized.

Boiler efficiency Same as combustion efficiency but heat radiation is accounted as a loss.

Combustion efficiency Momentary ratio of useful heat and fuel energy input. Energy losses are free heat in flue gas, fuel residues in ash, and incomplete gas combustion.

Downdraft combustion Wood log combustion principle where the hot gases are not discharged to the top, but the flames instead spread underneath the bottom of the combustion chamber or sideways and the combustion gases released are channeled into a combustion chamber located below or next to the fuel filling space.

Stand-alone furnaces These furnaces (stoves) emit their thermal energy to the surrounding space only.

Updraft combustion Wood log combustion principle where the combustion air (primary air) is channeled upward through the grate or from the bottom of the fire bed and thereby through the whole layer of fuel.

Definition of the Subject

The use of wood for the supply of heat in furnace systems with small to medium capacity has never really gone out of fashion, particularly in rural areas. Especially in recent years, a virtual renaissance in the use of wood for combustion purposes in the most diverse range of furnaces can be observed. Driven by continuously growing fuel costs for oil and gas from fossil resources as well as by public policy promoting the increased use of renewable energies in order to reduce greenhouse gas emissions, more and more already existing furnaces (mainly stoves) are being used more intensively. But also a considerable number of new systems are being installed (size of the market for small-scale furnaces in EU-27 approx. 3–4 million units per annum [3]). In many countries, more than half of the solid biomass used for energetic purposes is used in small-scale furnace systems with a thermal capacity below 1 MW. Small-scale combustion units, however, are at the same time one of the main source of particulate matter emissions. An improvement in existing system technology is therefore an essential challenge for the environmentally sustainable use of solid biomass in small-scale furnaces. For these reasons the present state of technology and current developments are presented in detail within this paper.

Introduction

Solid biomass fuels are used for a variety of reasons and different energetic purposes. Biomass is an energy carrier with a high potential for the reduction of greenhouse gas emissions, compared to fossil fuel energy, provided that the biomass is produced in a sustainable manner. Biomass is often regionally available or can be regionally produced as a source of fuel which can contribute to rural development as well as a more secure energy supply system.

Biomass is used for the supply of electricity, heat, and the production of biofuel. The use of solid biomass fuels – and wood in particular – for the supply of heat is the longest established form of energetic use. Even though the supply of electric power generated from biomass and the production of biofuels has increased considerably in recent years, in most countries of the world the majority of solid biofuels is used for the supply of thermal energy. Nevertheless some tendencies can be noted indicating that the combined generation of heat and power will significantly gain in importance, also in the lower capacity range.

Apart from the environmental debate surrounding the low-tech combustion of biomass in developing countries, emission levels in general and particulate matter emissions from biomass-fueled furnace systems in particular are also increasingly discussed in industrialized countries. Very low levels of emission have already been achieved in the case of large-scale combustion systems with several MW thermal capacity through regulatory stipulations and the corresponding refitting of plants for the implementation of emissions control measures. In contrast to this, there still exists considerable room for improvement in the case of small-scale systems below 1 MW thermal capacity, in particular with regard to stand-alone furnaces and biomass-fueled combustion systems. A number of countries such as Germany, Austria, and Switzerland have already lowered their emission thresholds for this segment of combustion plants, and other European countries and Federal States in the US are also contemplating the imposition of measures aimed at the reduction of emissions.

A comparison of emission levels made during certification of boiler systems in countries where this is a regulatory requirement indicates the gradual development toward lower values. This applies not only in respect of boiler systems but primarily also with regard to the further technological development of stand-alone furnaces (stoves). A significant reduction in the emission of air pollutants can therefore be achieved by using correspondingly advanced technology. Through investigation of the mechanisms leading to the creation of air pollutants and the introduction of specific measures for further reduction, clearly targeted and controlled progress in technical developments already has been and will continue to be achieved.

In this context, the basic principles for optimizing the processes for the combustion of solid biomass in small-scale furnace systems are presented below. Following on from this, the current state of development regarding different systems for combustion is analyzed. Together with an accompanying commentary on current levels of emission, this paper sets out in closing the perspectives concerning potential future developments.

Technical Approach

Combustion Requirements

A major objective should be to accomplish complete oxidation during the combustion process. This can be achieved by physical separation of the phases of pyrolytic decomposition of the fuel and the gasification process of the charcoal (coke) on the one side from the subsequent combustion of the products from the pyrolytic decomposition and gasification on the other side. The most important requirements for a complete conversion of fuel can be summarized as follows:

- Pyrolytic decomposition of the biofuel and gasification of the remaining carbon to CO , H_2 , CH_4 , C_nH_m , CO_2 , and H_2O . This is accomplished through:
 - Complete pyrolytic decomposition of the biomass fuel through sufficiently high temperatures throughout the whole cycle of reaction
 - Complete gasification of the carbon through good distribution and correct dosage in the supply of air (primary air) to the reaction zone
 - As little as possible disturbance to the fire bed being caused as a result of the recharging of fuel and removal of ashes
- Oxidation of the products released by the processes mentioned above; that is, gas phase oxidation of CO , H_2 , CH_4 and C_nH_m to CO_2 and H_2O . Complete oxidation of the fuel gases released takes place through:
 - Supply of oxidants (secondary air) in excess,
 - Sufficiently long retention time for the fuel gas/air mixture in the reaction zone
 - Sufficiently high combustion temperatures
 - Good amalgamation of fuel gases and combustion air through high turbulences
 - Limited retention time in the secondary combustion chamber, that is, approximation of the ideal distribution in a so-called plug flow

The requirement concerning the physical separation of the solid materials conversion process (with primary air supply to the fire bed) from the combustion process within the gas phase (with secondary air supply to the secondary combustion chamber) is therefore an essential prerequisite for a controllable combustion process. For this reason both air supply streams should be controlled independently. For solid biofuels, with their high level of volatile compounds, the separation of primary air supply and the secondary air supply into a specific combustion chamber is therefore an essential requirement for system designs. The primary air supply has an impact on combustion power output, whereas secondary air primarily serves to ensure a full oxidation of the combustible gases.

The technical combustion requirements for gas-phase oxidation described above are sometimes also referred to as the “3-T-Rule” for furnace design (time-temperature-turbulence); that is, retention time, combustion temperature, and intensity of amalgamation represent the essential parameters to be optimized [28].

The better the mixture of fuel gases with the combustion air, the lower the amount of excess air required at which the furnace can (almost) be operated without the discharge of noncombusted gases. A lower volume of excess air also results in higher combustion temperatures; surplus amounts of excess air on the other hand would lead to a cooling down of the system (and thus slowing down the reaction speed). To allow for a low volume of excess air it is essential to use slightly moist or wet biomass fuel. Because the energy consumed by the evaporation process of the water will tend to lead to a lowering of temperature levels in the combustion chamber and the resulting water vapor will additionally increase the volume of flue gases discharged and thereby increase further loss of thermal energy from the hot zone. At the lowest possible level of excess air, which is limited by the overriding objective of minimizing the emission of noncombusted elements (i.e., flue gas components that could be further oxidized), the level of efficiency in the performance of the systems would be at the highest [28].

In trying to optimize excess air supplies, a high combustion temperature can also be maintained by avoiding the unnecessary release of heat from the

combustion chamber. This is usually accomplished through the installation of thermal insulation refractory lining inside the primary and secondary combustion chambers. Insulation materials used for the lining of surfaces facing the open fire are, for example, fire clay, refractory concrete, lava clay or ceramic fiber materials [28].

As a general rule for most combustion, a principle does apply: The majority of available thermal energy is not (already) obtained in the combustion chamber, but captured later on from the heated combustion gases, in a heat exchanger which is separated from the combustion chamber. Early extraction of heat may be advantageous when using dry fuels, or in special areas of application if, for example, for the control of fire bed temperatures a cooling down effect by way of specific extraction of available thermal energy is desired (e.g., in the case of fuels whose ashes tend to slag). In grate-based furnace systems for such special fuels, water-cooled grates are used sometimes allowing to operate the system without excessive primary air being used for cooling purposes. In the combustion of dry fuels, the encasement of the combustion chamber with water-cooled walls may also be used to allow for the controlled extraction of heat.

Additionally, furnaces have to comply with applicable environmental regulatory requirements, whereby – also in the case of small-scale systems – secondary measures are sometimes introduced (Section on “Emission of Boilers”). The key to arriving at a minimal emission of polluting substances during operations is primarily to maintain optimal operating conditions; this applies in particular with regard to an optimized fuel-air-ratio, and the use of appropriate control mechanisms is required for this purpose. A complete conversion of fuel materials does in most cases go hand in hand with low-emission values.

Differences Between Manually and Automatically Charged Furnaces

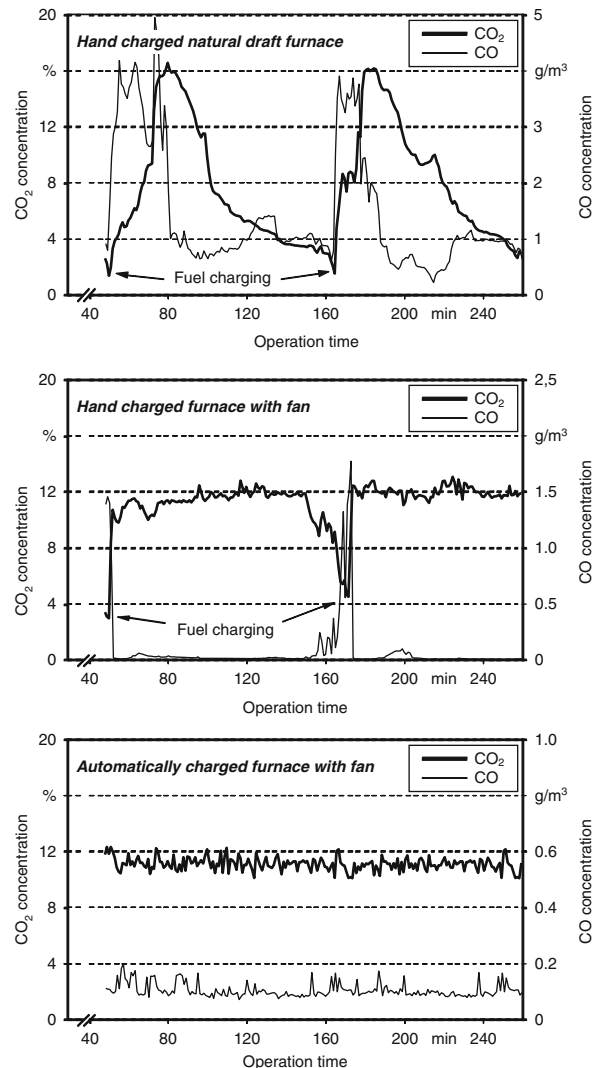
Combustion technology distinguishes between manually charged and automatically charged furnaces. Hand-charged furnaces are generally considered systems where fuel is supplied to the combustion chamber intermittently. In contrast to this, the fuel supply in

automatically charged furnaces is transported continuously into the combustion chamber. Thus the furnace is charged as evenly as possible. In the following section, the differences in combustion process between intermittent and continuous charging are initially described in more detail, followed by an introduction of the actual systems technology.

Intermittently charged furnaces demonstrate marked variation of the combustion parameters during the chronological process of a burn-off. This applies in particular for systems without fan (“natural draft furnaces”), which represent the majority of stand-alone furnaces (section on “[Stove \(Stand-alone Furnaces\)](#)”), since the general conditions for combustion between the two recharging intervals do change considerably.

With the loading of every new batch of fuel, the still cold and potentially not yet fully dried new fuel, combined with the opening of the charging trap, the furnace will initially cool down. In the case of updraft combustion, the space available in the combustion chamber decreases during the recharging process and subsequently increases again gradually during the ensuing continuous combustion process. Therefore, this process is also referred to as “batch combustion.” With changes in the volume of space available in the combustion chamber, the corresponding retention times for the combustible gases formed through pyrolytic decomposition and gasification also do change in many furnace designs. These constantly changing conditions for combustion can be monitored by reference to the concentration of the meanwhile generated carbon dioxide (CO_2) and carbon monoxide (CO) in the flue gas (Fig. 1, top) [28].

For optimum efficiency in combustion, the air supply needs to be adjusted during the different phases of combustion. The use of a fan system is recommended for this purpose. Through suitable features in the design of furnace systems an attempt is made, furthermore, to achieve a combustion cycle which is as continuous as possible, with constant performance and low levels of emission. The recharging of fuel and the changing volume of space available in the combustion chamber should have as little as possible interfering impact on this process. A combustion principle in which these demands have been met, quite efficiently also in the case of hand-charged furnaces, is the so-called downdraft combustion. In this system, only the



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 1

Typical patterns of carbon dioxide (CO_2) and carbon monoxide (CO) concentrations in flue gas during natural draft combustion (masonry heater) (Fig. 1, top), a hand-charged furnace with fan (log wood-burning furnace, updraft combustion without grate) (Fig. 1, middle) and an automatically charged furnace (wood chip furnace) (Fig. 1, bottom) at operating temperature conditions (heating-up phase not illustrated; different scales for CO values in separate illustrations) (see [3])

lowest layer of the fuel bed takes part in the combustion process (section on “[Principles and Operating Systems](#)”). The development of CO_2 and CO

concentrations in the flue gases (Fig. 1, middle) show, that a largely stable and consistent level of operating conditions, approaching those of automatically charged furnaces, can be achieved based on such a design.

Automatically charged furnaces will generally be fired with fuel easily be formed into batches; such a fuel is produced if necessary through shredding or pelletizing. Usually these fuels are continuously and automatically supplied to the combustion chamber, so that the furnace system can be adjusted to a constant and largely balanced level of performance. Continuity in the supply of fuel allows for an adjustment in the supply of air, specifically adapted to the particular amount of fuel fed into the system, with temperatures in the combustion chamber, at the time, remaining at a constant level [28]. This kind of operating mode ultimately leads to steady and low levels in the emission of noncombusted compounds (Fig. 1, bottom).

Automatic charging, using loose fill fuel materials, also makes it possible to adjust the fuel supply automatically to changing patterns in the demand for thermal energy. As a result of this, automatically charged systems are also capable of operating at only partial load over comparatively long periods (approx. 30 up to 100% of nominal thermal power output). For the bridging of phases with low demand for thermal energy buffer heat storages can therefore be scaled down or – under certain circumstances – be omitted altogether.

Combustion Principles and Furnace Types

Manually Charged Wood Furnaces

Hand-charged furnaces represent the most important group of small-scale systems. Therefore the technical principles and different types of design for this group of systems are described below, in greater detail.

Principles and Operating Systems Hand-charged wood-burning furnaces are fueled at specific intervals – according to capacity and filling space – with smaller or larger charges of solid biofuel. As a result of this, different phases in the combustion cycle do occur and distinctions are made between a start-up phase, the subsequent phase at operating temperatures and finally

the phase of combustion of the remaining charcoal. Depending on the system (fan assisted or natural draft) these phases are quite distinct in their characteristics (Fig. 1), and disruptions to continuity in the process of combustion may result in the drawbacks referred to above (e.g., regulation of the optimal amount of air supply).

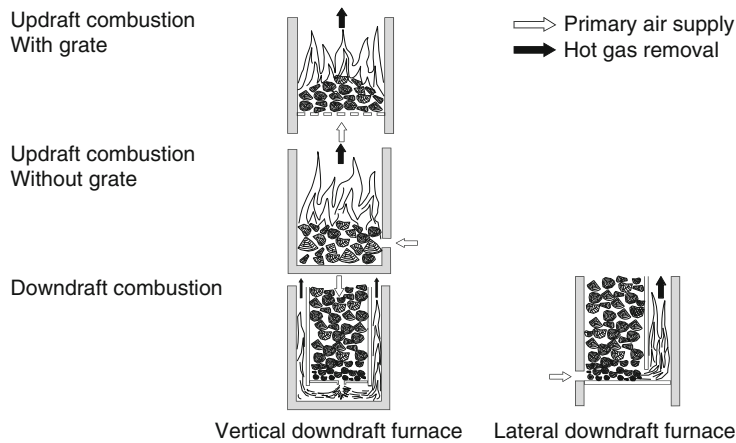
Nevertheless, manually charged furnaces must be operated at low levels of emission. Apart from optimization of combustion technologies, the correct control and management of the system (i.e., prevention of errors in operating the system) as well as use of the right fuel type are essential prerequisites (i.e., the right choice between untreated, air dried log wood or pellets produced from untreated wood and without additives). The combustion of pieces of particle board remaining from the ordinary production process and treated wood, painted or lacquered wood, as well as combustible waste material (e.g., waste paper, plastic packaging materials) is, generally speaking, not allowed for small-scale furnace systems. Such substances lead not only to high and extremely toxic emissions and toxic residues, but could also reduce the useful lifespan of the plant considerably.

Hand-charged wood-burning furnaces can be distinguished by the following characteristics:

- Construction design: stand-alone furnaces, enhanced stand-alone systems, and central heating boilers
- Draft systems: natural draft or fan-assisted draft
- Grate system: furnaces with or without grate
- Position of grate: shallow combustion or full load combustion
- Combustion principle: updraft combustion with grate, updraft combustion without grate, downdraft combustion, and/or lateral downdraft combustion

The most important distinguishing features are the combustion principles described in more detail below. Their use in the different types of system design is outlined in the subsequent sections on “[Stoves \(Stand-alone Furnaces\)](#),” “[Enhanced Stoves](#),” and “[Central Heating Boilers](#).”

System designs for the different combustion methods commonly employed in hand-charged furnaces are



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 2

Combustion principles for hand-charged wood-burning furnaces (secondary air flow and secondary combustion chamber not illustrated here)

illustrated in Fig. 2, whereby the two first named systems often cannot be clearly distinguished from one another. They are therefore not always treated as separate individual combustion systems. They are often considered as different operating versions of one and the same system. Since the concepts for updraft combustion with grate and updraft combustion without grate have been developed in different areas – that is, for coal (updraft combustion with grate) and for wood-burning furnaces (updraft combustion without grate) – and different plants with correspondingly varying features are used in practical application, these two combustion principles are covered separately in the following sections.

Updraft combustion with grate. Here the combustion air (primary air) is channeled through the grate or from the bottom of the fire bed and thereby through the whole layer of fuel. Ignition is handled from below and the fire bed develops and spreads over the grate underneath the remaining supply of fuel. Through this process, the entire amount of fuel is heated up and brought simultaneously into a state of reaction (Fig. 2, top). This also represents the major drawback of this system. Because the adjustment of the amount of combustion air supplied to the different levels of combustion gases released proves to be rather difficult. This applies especially if fuel is charged in very large batch sizes and as a result a separation between the zone of

the pyrolytic decomposition and the secondary combustion is no longer possible. Therefore these types of furnaces are best operated through frequent charging with small amounts of fuel, in order to achieve an as constant and balanced combustion process as possible. However, the conditions for combustion change with every charging process (as well as throughout the course of the combustion cycle). Therefore, this type of combustion – with grate or without grate – is sometimes also referred to as charge combustion.

Updraft combustion with grate represents the classic combustion principle for short-flamed coal fuels. The proportion of volatile substances (“combustion gases”) formed during pyrolytic decomposition is comparatively low for coal, whereas the largest proportion of thermal energy produced is due to the oxidation of carbon. Similarly, the usually missing clear separation between the zone of pyrolytic decomposition and gasification, as well as the oxidation zone, generally turn out to be less disadvantageous in the combustion of coal fuels. In spite of the problems outlined above, the principle of updraft combustion with grate is, so far, used preferably for stand-alone furnaces (especially chimney stoves and fireplaces), even when using wood fuels (characterized by a high content of volatile substances). This is also because easy removal of the ashes is made possible through the grate and ash box. In modern firewood boiler systems, however, the

principle of updraft combustion with grate is usually no longer employed.

Updraft combustion without grate. In contrast to updraft combustion with grate, the combustion air (primary air) in updraft combustion without grate is supplied laterally to the fire bed zone (Fig. 2, middle). The first charge of fuel is ignited from above, and the fire bed is formed in this process during the initial phase of combustion. As the flames and hot gases emitted during the pyrolytic decomposition can rise unhindered, the high operating temperatures required in the secondary combustion chamber for complete combustion are reached comparatively fast, while the fuel supply gradually heats up from the top to the bottom. The release of gaseous substances is therefore slowed down. The wood supply burns more evenly and controlled from the top down to the bottom, that is, the same as would be the case in an updraft furnace with grate. It would be a disadvantage if the furnace is not provided with an appropriate secondary air supply, as the space available in the combustion chamber will vary with the reduction in the level of fuel supplies, so that the retention time for gases (produced by the pyrolytic decomposition and the gasification) in the secondary combustion process will be continuously changing. The longest retention time thus occurs at the end of the combustion cycle and not at the start, as would be desirable from the perspective of looking to achieve an optimum combustion process.

New fuel – if applied – is placed on the remaining fire bed during recharging; and the subsequent combustion cycle is therefore similar to that of updraft combustion with grate furnace system. Small volumes of fuel and frequent intervals in the recharging of the systems are of advantage in updraft combustion without grate, as well. However, since combustion air (primary air) is channeled over and not through the fire bed, excessive rekindling of embers (in the ashes) can be avoided. These furnaces are therefore frequently designed without grate in order to avoid unwanted supply of air. The removal of ashes on the other hand can only be performed when the system has cooled down.

The principle of updraft combustion without grate is commonly used in stand-alone furnaces (e.g., masonry heaters; Fig. 5). As is the case in updraft systems without grate, usually no fans for additional

air supply are installed in updraft furnaces without grate (“natural draft operation”). The amount of air supply is regulated by adjustments made to the air supply inlet and chimney flaps.

Furnaces using updraft combustion with or without grate rarely exist as “purebred” systems, but are usually combined in some form or other. For the use of different kinds of fuel (e.g., firewood, wood pellets), these types of stand-alone furnaces (e.g., chimney stoves) can often be switched from one operation mode to another, so that they usually work on the basis of updraft combustion with or without grate. In such combined furnace systems, coal fuels (e.g., briquettes) are used in updraft combustion with grate (predominantly using grate air), whereas for wood fuels the combustion air is supplied laterally or from above while the grate air supply is locked. But small amounts of grate air can also be of advantage in the combustion of wood fuels, as they support the complete combustion of charcoal residue.

Vertical or lateral downdraft combustion. In contrast to the two methods of combustion described above are heat gases in downdraft combustion not discharged to the top, but the flames instead spread underneath the bottom of the combustion chamber or sideways (“downdraft furnaces”). Consequently, the respective lowest layer of fuel takes part in the combustion process. The combustion gases released in the area of primary air supply are channeled into a combustion chamber, located below (“vertical downdraft combustion”) or next (“lateral downdraft combustion”) to the fuel filling space, by means of fan supported draft, and do reach the stage of complete combustion with the aid of secondary air supply (Fig. 2, bottom). In the case of lateral downdraft combustion, part of the primary air can also enter through a bottom grate, which allows for the removal of ashes and furthermore supports complete conversion of charcoal residues.

The wood placed above the fire bed zone serves as a fuel reserve, which will automatically slip lower during combustion of the charge, thereby allowing for a quasi-continuous recharging with fuel supplies. In contrast to updraft combustion systems, with or without grate, the amount of fuel placed in the combustion space using the downdraft principle is essentially not important. It does, however, have an impact on “operating comfort,” as the need for constant recharging can

be eliminated by way of depositing larger amounts of fuel supplies in the filling space; the combustion cycle for a charge in this type of firewood furnace, for example, can run up to 5 h and more.

The downdraft combustion principle allows for relatively continuous pyrolytic decomposition and gasification of fuel materials. This makes it easier to adjust the combustion air flow required for the amount of combustion gases released, allowing for good combustion and high levels of efficiency to be reached.

Due to the advantages outlined above, the downdraft combustion principle is by far the most commonly used system in log wood-fired central heating boilers (section on “[Central Heating Boilers](#)”). In contrast to updraft combustion systems with or without grate, however, reinforcement of air supplies through the use of a ventilation system (suction or pressure blowers) is usually an essential requirement. This is one of the reasons – apart from people’s esthetic desire to be able to watch the flicker of the flames – why the principle of downdraft combustion is used only rarely in stand-alone furnaces today.

In plants operating on the basis of the downdraft principle, coarse wood chips can generally be used as well, apart from log wood. Unlike updraft combustion, however, there is the risk of hollow combustion (i.e., the formation of “bridges” above the fire bed). This can lead to correspondingly higher levels of emission, as a result of disruptions in the process of complete combustion.

[Table 1](#) summarizes customary hand-charged furnaces, including details concerning typical heating performance, the combustion principle employed and, where appropriate, various distinguishing characteristics. The different types of designs listed are described below in more detail.

The hot combustion gas emitted from the combustion chamber is usually referred to as heat gas, given its hot state. Following the emission of thermal energy into the surrounding space or into the boiler, this combustion gas is referred to as flue gas, once it has cooled down and is discharged into the environment via the chimney (or flue stack).

Stoves (Stand-alone Furnaces) Due to their design, stand-alone furnaces (stoves) emit their thermal energy to the surrounding space only. This usually happens

through the radiation of heat and, to a lesser extent, further by way of convection. Stand-alone furnaces which belong to this category of design include open or closed fireplaces, cast iron stoves, chimney stoves, masonry heaters (including masonry convection heaters, tiled stoves), as well as wood-burning kitchen stoves and pellet stoves (see summary in [Table 1](#)). They are usually only used occasionally (i.e., as a supplementary source of heating).

One can differentiate between separate types of stand-alone furnaces by way of a variety of criteria ([Table 2](#)). For example, they can be grouped into shallow combustion and full-load combustion systems.

- In the case of shallow combustion, only a single layer of firewood is loaded in each recharging process (in the case of kitchen stoves and central heating boilers, shallow combustion is additionally defined by the distance between the grate and the cooking surface [4, 7]). Shallow combustion systems include, for example, open and closed fireplaces, chimney stoves, as well as kitchen stoves and masonry heaters in cooking mode (summer mode, [Fig. 8](#)). For these types of furnace systems, the typical load of fuel for each charge ranges between 2 and 5 kg (for cooking mode even less than 2 kg).
- Full-load furnaces are, in contrast to this, suitable for larger fuel charges; this ensures a certain minimum combustion cycle at rated thermal output values (“permanent combustion stoves” [5]; for example, kitchen and masonry stoves in heating or winter mode, or certain types of standard masonry heaters). The volume of individual charges in this case is likely to be in excess of 5 kg fuel per load.

Besides this, there are a large number of further criteria available to differentiate between systems ([Table 2](#)). However, they do not always allow a clear distinction between different designs. The reason for this lies in the diversity of modifications made. Also, mixed systems of existing furnace designs are now available, which make a clear and definitive assignment to one category or another somewhat difficult. As a result of this, a variety of names and categories have become common use, and a certain degree of ambiguity, in terms of terminology used in the following remarks, can therefore not be avoided completely.

Biomass Energy Heat Provision in Modern Small-Scale Systems. Table 1 Construction design and characteristics of hand-charged wood furnaces

Type	Heat power output in kW	Combustion principle	Characteristics
<i>Stoves and fireplaces (thermal energy primarily for space of installation – depending on design)</i>			
Open fireplaces	0–5	Updraft combustion with/without grate	With and without hot air circulation, not suitable for permanent heating
Enclosed fireplaces	5–15	Updraft combustion with/without grate	With hot air circulation, display window
Cast iron stoves	3–10	Updraft combustion with/without grate	Free standing wood furnace charged in the domestic/living area where installed
Chimney stoves	4–12	Updraft combustion with/without grate, downdraft combustion (rare)	Same as cast iron stove, with display window
Masonry (“tiled”) stoves – slow release thermal storage heaters	3–15	Updraft combustion with/without grate, downdraft combustion (rarely)	Slow radiation of stored heat over a 10–24 h period through radiation (masonry heater), or with convection air supply (hot air masonry heater)
Kitchen stoves	3–12	Updraft combustion with/without grate, downdraft combustion	Heat for cooking (primary use), thermal heat or bench heating (secondary uses)
Pellet stoves ^a	2.5–10	Cup burner/hearth furnace (for wood pellets)	Automatically charged, controlled fuel and air supply (fan), re-charging required approx. every 1–4 days
<i>Enhanced stoves (thermal energy also for areas other than place of installation – depending on design)</i>			
Central heating kitchen stoves	8–30	Updraft combustion with/without grate, downdraft combustion	Supply of thermal energy for cooking, central heating and hot water supply purposes
Enhanced masonry stoves, fireplaces and chimney stoves	6–20	Updraft combustion with/without grate	Water – heating circuit or closed hot air circuit (hypocaust heating system)
Pellet stoves ^a with water jackets	Up to 10	Cup burner/hearth furnace (for wood pellets)	also suitable as sole source for domestic heating (e.g., low-energy construction)
<i>Central heating boilers (use of thermal energy only outside the place of installation)</i>			
Log wood boiler	10–250 (max. 800)	Downdraft combustion, updraft combustion with grate (rare)	Logs up to 1 m in length, natural draft or blower supported boilers, thermal storage (buffer) required

^aPellet stoves, in terms of design, would be considered automatically charged furnaces and are therefore reviewed as to characteristics and functions in section “[Pellet Furnaces](#)”; however, they have been listed in this section since they belong to the category of typical stand-alone furnaces/room heaters

Although versions with exterior air supply do exist for almost all categories of design, today stand-alone furnaces generally still are operated using air extracted from the room or space where they are installed.

Critical operating conditions, as a result of air being extracted from the room, for systems using chimney draft are generally to be expected only if – as it could be the case for modern building designs with tightly

Biomass Energy Heat Provision in Modern Small-Scale Systems. Table 2 Distinguishing features of independently operated stand-alone furnaces (stoves)

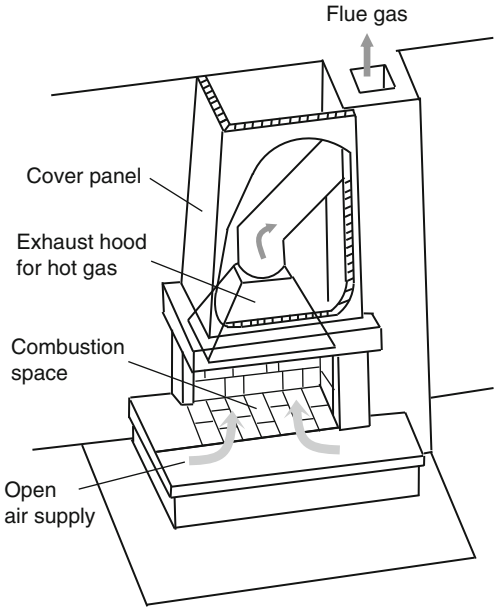
Design/ installation	<i>Assembled (partly using prefabricated components) and installed on site by specialist contractors, fixed permanently</i>	<i>Industrially produced complete units, can be moved</i>
	Open/enclosed fireplaces, masonry heaters (with/without grate), tiled stoves	Cast iron stoves, chimney stoves, pellet stoves, kitchen stoves
Storage capacity	<i>Low to medium</i>	<i>High ("buffer stoves")</i>
	Open/enclosed fireplaces, cast iron stoves, chimney stoves, pellet stoves, masonry heaters (with grate), kitchen stoves, enhanced stand-alone furnaces	Masonry heaters/stoves (without grate), cast iron stoves or chimney stoves with large tiled or soapstone exterior surfaces
Charging	<i>Hand charged</i>	<i>Automatically charged</i>
	Open/enclosed fireplaces, masonry stoves/convection heaters, cast iron stoves, kitchen stoves	Pellet stoves, pellet boilers for central heating
Typical operating cycles	<i>Longer operating cycles^a</i>	<i>Usually shorter operating cycles</i>
	Enclosed fireplaces, cast iron stoves, chimney stoves, pellet stoves, masonry convection heaters, enhanced stand-alone furnaces	Standard masonry heaters (1 h combustion cycle, minimum 12 h release of thermal energy/heat), open fireplaces, kitchen stoves
Supply of thermal energy	<i>Primarily radiant heat</i>	<i>Primarily convection heat transfer</i>
	Standard masonry stoves, cast iron stoves and chimney stoves without circulation vents, kitchen stoves and pellet stoves	Masonry convection heaters, chimney stoves with circulation vents, stand-alone furnaces with water jackets

^aFrequent daily or permanent combustion cycles through repeated charging

fitting doors and windows – the otherwise available “combination of combustion air” (i.e., the overall volume of air available from other rooms and spaces connected to the room of installation by way of air circulation; approximately 4 m³ of ambient air per kW nominal heat power output) should turn out to be insufficient [33]. This is most likely to occur in the case of open fireplaces, which are operated at high levels of excess air.

However, problems may also occur if low-pressure systems are used for the purpose of room ventilation, as they can limit and restrict the natural draft of the chimney (e.g., kitchen vents, controlled ventilation, air-conditioning). In such cases, furnaces without fan need to be supplied additionally with external air.

Open fireplaces. In contrast to all other stand-alone furnaces, an open fireplace has a combustion chamber which is open on one side (exposed to the room or living space where it is installed). The back and partially the sidewalls are usually closed by brickwork (Fig. 3). It is constructed either using fireclay components or



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 3 Open fireplace [18]

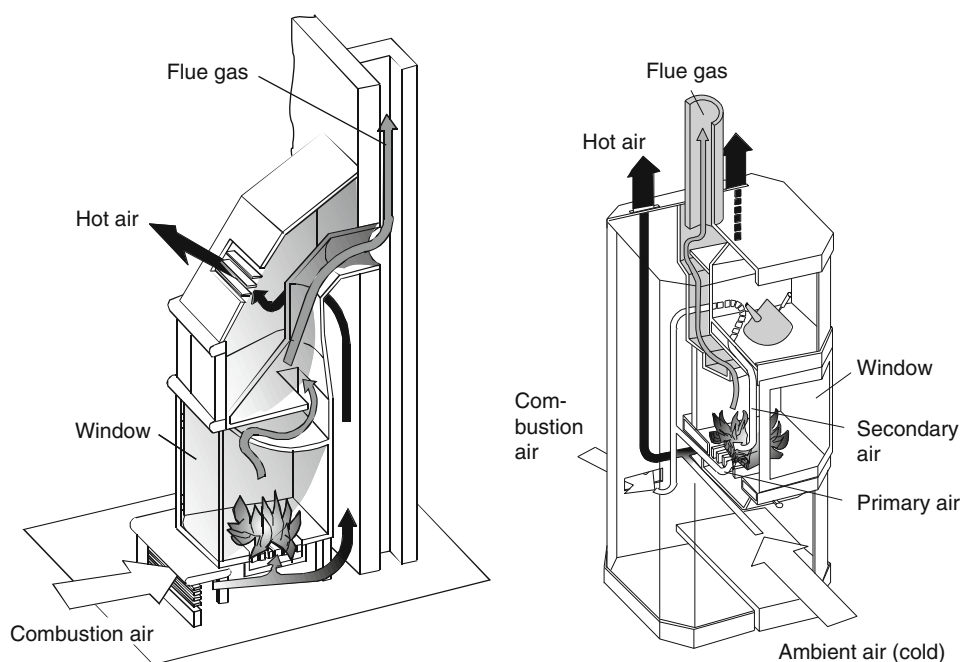
prefabricated units (e.g., an iron fireplace insert). A controlled and graduated supply of combustion air is not possible for this type of furnace design. In order to prevent the potential emissions of gases into the living space, such furnaces are operated at very high levels of excess air. The necessary combustion air supply is taken from the surrounding living space; in some cases, additional external air is supplied through separate air ducts.

In the case of open fireplaces, the often found use of a stand-alone furnace as an additional source for the provision of heat tends to be only of secondary importance; this type of furnace primarily serves to improve the esthetic “quality of living.” Thermal energy is released principally through heat radiation. Due to the significant volume of air, required combustion efficiency generally tends to be poor (i.e., comparatively high combustion temperatures, resulting in low efficiency and a high level of air-pollutant emission); and it is for these reasons that the use of open fireplaces as a source of permanent heating is prohibited, for example, in Germany. The use of open fireplaces, and to some extent of other

stand-alone furnaces, has therefore been banned in many residential areas.

Enclosed fireplaces. A fireplace insert can be equipped with an automatically closing glass door or glass screen. Such a system is called enclosed fireplace; other customary names used for this type of installation are “heating place” or “cheminee.” These heating inserts comprise a combustion chamber with an ash box, a flue gas collector, hot gas ducts, and an exhaust hood. In contrast to open fireplaces, these furnace designs do have an enclosed combustion chamber (Fig. 4, left), and the supply of combustion air can thereby be better controlled and regulated. Because of this, there will be an increase in room temperature and consequently a significant improvement in heating performance and combustion efficiency; and most importantly, no further increase is caused to air circulation in the room. In order to take advantage of these benefits existing open fireplaces can be refitted with so-called chimney sets.

The thermal energy generated in enclosed fireplaces is largely emitted through radiation. Many enclosed systems are additionally fitted with convection ducts



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 4

Working principles of an enclosed fireplace (left) and a chimney stove (right) [32]

and hot air pipes through which air can be distributed – if necessary with the support of a blower system. Thus the supply of heating for adjacent rooms is also possible (section “Enhanced Stoves”).

Cast iron stoves. Cast iron stoves differ from open or enclosed fireplaces in as much as they are installed free standing in the living area; they are usually cast iron stand-alone furnaces (also called “iron stoves,” although different versions with outside mantling of tiles or soapstone do exist). The fuel is loaded through the upper of usually three doors into the combustion chamber, which generally are lined with fireclay bricks in the lower combustion areas. Ashes having dropped through the grate are caught in the ash box, which can be removed for disposal through the lower door. Cleaning of the grate can be handled via a further door located at the level where the grate is installed. For ease of operation, the design of the grate allows vibrating (manual operation).

Free-standing stoves generally work on the basis of updraft combustion without grate (see Fig. 2). The proportion of air supplied from above can usually be regulated through manually operated flaps or dampers, so that the amount of excess air serving as secondary air supply is predominant. In basic versions of this design, combustion is simply controlled or adjusted by way of a reduction in overall air supply, or by means of a slide damper or rosette installed in the opening designated for the removal of ashes. These stoves may also be clad with tiles or natural stone, thereby increasing buffer mass and at the same time regulating the emission of heat more evenly.

Chimney stoves. The present day version of the cast iron stove is the chimney stove. It can also be installed (free standing) in the living area, but is fitted with a single airtight closing door with screen (Fig. 4, right).

The combustion principle corresponds to that of the cast iron stove. Grate combustion air (primary air) or air from above (secondary air supply) is injected according to the type of fuel used in differing proportions. Air supply from above, however, serves as additional “cleaning air.” Therefore, this air is channeled from above alongside the glass screen, in order to counteract the potential precipitation of soot or dust residues.

Similar to cast iron stoves, chimney stoves do release the majority of their heat via radiation (approx.

50%), whereby surface temperatures can be as high as 250°C. In the event that a convection sleeve has been installed (air circulation vents) effective radiation may drop to as little as 10% of the rated thermal energy output [33], whereby the door with glass screen is responsible for the remaining proportion of radiation. The specific burnout rate for chimney stoves has been defined at a maximum value of 4 kW/m² [5]. Mass per kW heating performance usually ranges between 13 and 26 and overall loads of 40–80 kg/m² heating surface have to be allowed for [33].

Chimney stoves, similar to fireplaces or cast iron stoves, are preferably used during transitional seasonal periods or as auxiliary/supplementary heating. Recharging intervals are short, since only one layer of fuel is loaded – compared to the use of coal briquettes – which will combust in a relatively short period. Stoves which are exclusively designed for the use of wood are therefore considered to be “not suitable for permanent operation” [5].

Masonry stoves/heaters. The main characteristic of masonry slow releasing heaters is the comparatively large volume of storage/buffering capacity in relation to the amount of thermal energy generated by the system. Hot gas is channeled by means of brickwork ducts through the buffering mass, which generally consists of cement plaster, tiles, clay, and mortar – and fireclay or soapstone. Correspondingly, terms like tiled stove, masonry heater, masonry convection stove, and soapstone oven are commonly used in describing these systems. The surface releasing the heat, primarily in the form of thermal radiation, will also be comparatively large so that surface temperatures will usually remain relatively low. For a medium-size masonry heater, these temperatures will range from 70°C to 120°C. Depending on thickness of the walls, the values for thermal radiation will range from 0.7 (heavy duty design) to 1.2 kW/m² (compact design) [33]. Although a variety of industrially prefabricated components are used today in the construction of this type of stove, it remains a system requiring considerable amounts of skilled craftsmanship from a stove builder for installation of the brickwork furnace on site.

The original design for a slow heat-releasing stove is the standard masonry heater of brickwork and plaster, with a weight in excess of 1 t [8]. Today’s designs mostly use prefabricated sets for the furnace and heating ducts

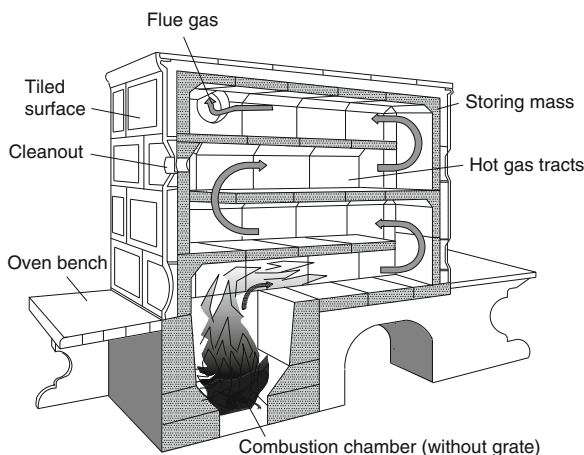
consisting of special design fireclay brickwork and metal components (front plate for the stove with filling door and openings for air supply, grate insert).

The standard masonry stove (Fig. 5) works according to the principle of updraft combustion without grate principle (Fig. 2). The combustion chamber and size of the secondary heating surfaces (hot gas tracks) have to be adapted to one another in such a way that the temperature of the flue gas emitted through the chimney should typically range between 160°C and 200°C. The storage mass is frequently equivalent to the amount of thermal energy released by one single charge of fuel (fired from above), so that no additional supply of wood has to (nor should it) be placed on top of the gradually reducing fire bed. Due to its substantial storage mass, a cold masonry stove heats up rather slowly. However, the stove also continues to radiate heat long after the embers have died down. Standard masonry stoves are therefore less suitable for “spontaneous use.” In modern versions it may be possible to automatically regulate the air supply (e.g., through electronic control of the air vents), but due to the inertia of the system, these means of control remain limited.

Slow heat-releasing stoves typically also require considerable amounts of space. This is why a variety

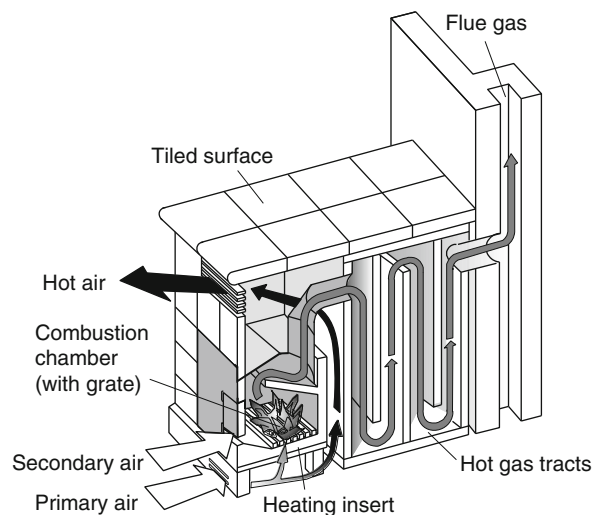
of medium- and smaller-size versions are available on the market, including, among others, the masonry convection heater (“tiled stove”) as well (Fig. 6).

In comparison to the conventional slow heat-releasing stove, the warm air convection heater (“tiled stove”) usually has less storage mass. This is especially true if it is not fitted with brickwork tracts. A cast iron heating insert (a so-called tiled-stove insert) is used. Around this insert, the brickwork casing (e.g., tiled walls) is installed allowing for a specific distance to the insert. Open-air ducts are installed at the plinth area of the tiled walls, so that cold air from the room can flow behind the tiling of the stove, where it is heated up, rises, and then leaves the air tract through hot air vents installed at the top of the stove. The higher the proportion of thermal energy released through this convection process, the lower the amount of thermal radiation emitted through the tiles. Many masonry convection heaters are additionally fitted with a secondary heating box made of cast iron, sheet steel, or ceramic tiles, which is again enclosed by a back ventilated tile casing and which can account for around 20% of thermal radiation. It often serves also as an additional place for the separation of fly ash. A secondary heating box can also be installed in an adjacent room, so that the stove heater is turned into



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 5

Working principle of a standard masonry heater with lateral brickwork tracts [14] (From KSW Kachelofen GmbH, Germany)



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 6

Working principle of a masonry convection heater (“tiled stove”) with vertical brickwork tracts [14]

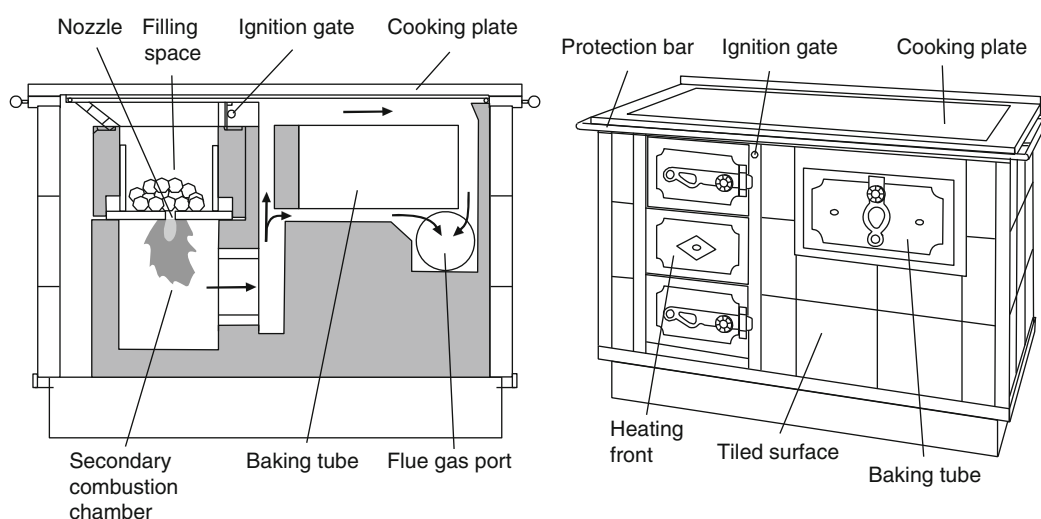
a multiple-room heating system (section “Enhanced Stoves”).

Masonry convection heaters fitted with brickwork tracts, however, can also have a comparatively high storage capacity (Fig. 6), so that there is somewhat of a moving transition to radiation-based heating systems. Similar to cast iron and chimney stoves, versions with or without grate can be designed. Tiled stoves can also be fitted with suction fans and flue gas–regulated control of combustion air supplies (microprocessor control system). Modern masonry stoves may also be fitted with glass screens so that they can offer an appearance similar to that of an enclosed fireplace or a chimney stove. In certain design types, the combustion air is supplied via an external air duct in order to allow for heating operations regardless of room air conditions.

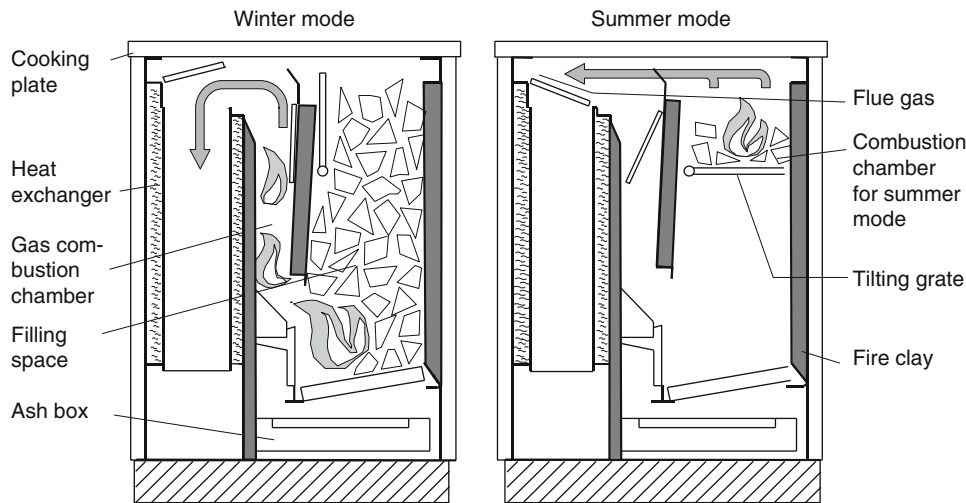
Kitchen stoves. The kitchen stove represents a type of design taking in particular care of the needs of such communities and households, where the kitchen is the center of domestic life. Even though the number of newly installed kitchen stoves is meanwhile declining considerably, they are still one of the most important types of stand-alone furnaces. Kitchen stoves are available as industrially produced, complete units, or in the form of more or less prefabricated building-sets ready for on-site installation (e.g., tiled kitchen stoves).

Natural draft–operated kitchen stoves work according to different combustion principles. The latest developments use downdraft systems in the form of vertical downdraft combustion (Fig. 7). For the heating-up stage, an ignition gate is installed which opens up a shortcut for the hot gas from the filling space (underneath the cooking plate) to the flue gas port. During normal operation, the flame is directed downward into the secondary combustion chamber whereby secondary air is supplied through the nozzle. The hot gases flow underneath the cooking plate and around the baking tube, and subsequently pass on in the form of cooled down flue gas into the chimney. In this type of system, the basic principles of efficient combustion can generally be taken into account.

However, the principles of updraft combustion with grate or lateral downdraft combustion (Fig. 2) are also used quite frequently, whereby in these cases the cooking plate is again heated up by the hot gases channeled right underneath the stove-top surface; with the aid of flaps, a potentially fitted baking tube can be heated as well. Some of these stoves can be switched from cooking mode to heating mode, changing from updraft combustion with grate to the downdraft combustion principle (Fig. 8). To ensure that the fire does burn as closely as possible to the cooking plate (in cooking mode) the “cooking combustion chamber” is kept shallow



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 7
Kitchen stove with downdraft combustion [18]



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 8

Modern central heating furnace with downdraft combustion: (left) winter mode for heating and cooking, (right) summer mode for cooking only [18] (From Tiba-Müller AG, Schweiz)

(“shallow combustion”) through the adjustment of the tilting grate to an appropriate height. If the stove is to be used for heating during winter, the grate is tilted downward, so that the whole of the filling space and/or space of the combustion chamber above the second grate, which is located underneath, can be utilized. This allows for almost doubling the output of heat due to the increased amount of heat exchanger surface now available (Fig. 8). If the stove is fitted with a grate whose position can be changed by means of a lifting device, the switch from summer to winter mode can also be made while the system is in operation.

In winter mode, the enlarged filling space often allows for the use of larger pieces of wood or logs, compared to the restraints imposed by the relatively tight combustion space available during “cooking only mode.” Most heating stoves do have separate primary and secondary air supplies as well as other features, albeit limited, for the adjustment of efficiency and performance. Combined kitchen/tiled stove versions are also available where, with the aid of diversion traps, the hot gases are redirected from stove operations into masonry heater tracts (including those potentially located in adjacent rooms).

Enhanced Stoves In the transitional area between stand-alone furnaces and central heating systems,

there are a number of hybrid systems and special designs available, which have evolved from stand-alone heaters and stoves. In these systems, only part of the available thermal energy generated is released to the surrounding space and/or utilized for, for example, cooking purposes. By installing an additional water heat exchanger, additional heat can be fed into a heating circuit and/or can be used for tap water heating. If required, thermal energy can also be discharged by hot air which is directed via special air ducts, either directly (in the form of convection heat) or acting as a medium for the transfer of thermal energy, to large-scale heating surfaces (e.g., back ventilated tiled walls) in adjacent rooms (hypocaust and/or air central heating systems). These types of enhanced stand-alone furnaces are described in more detail below.

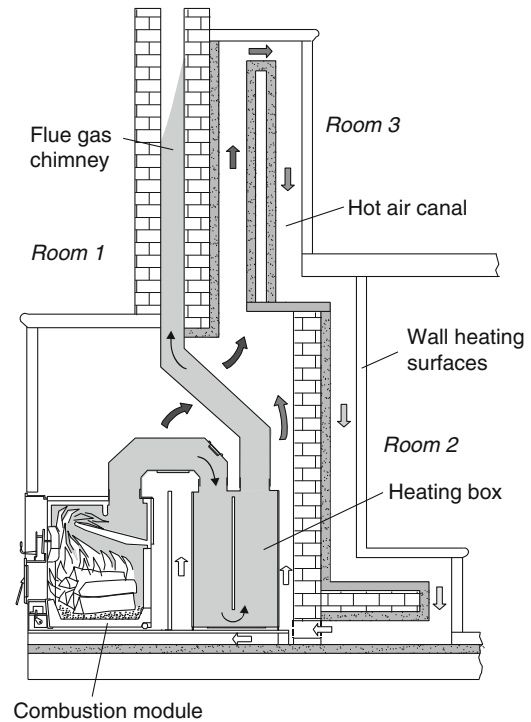
Central heating kitchen stoves. A large proportion of the wood-burning stoves currently in use do not just serve for cooking, baking, and kitchen heating purposes. They also supply hot water for the central heating system and for industrial water. In these types of central heating furnaces, which are available as firewood-burning systems as well as automatically charged pellet central heating boilers, part of the combustion chamber is encased by water jackets and additional heat exchangers are installed inside the hot gas tracts (Fig. 8). Excessive heat can be utilized for heating

up of a heat storage acting as a temporary buffer. The same marginal conditions, essentially, do apply as for hand-charged central heating systems.

Central heating stoves are either used for full-fledged domestic heating systems or as complementary furnaces. They have to be able to meet the safety relevant technological norms and standards applicable for central heating system boilers. They are therefore fitted, for example, with thermal control systems for protection against overheating. These are mechanical devices, controlled by flow temperatures, which will open up the drainage system in the water circulation of a safety heat exchanger connected to the system once a certain level of flow temperature has been reached (overheating), in order to discharge any excess thermal energy.

Central heating stoves can reach an overall efficiency rating of at least 65%, and the thermal radiation in the space where the unit is installed is not accounted for as a loss [4]. Ashes are removed manually.

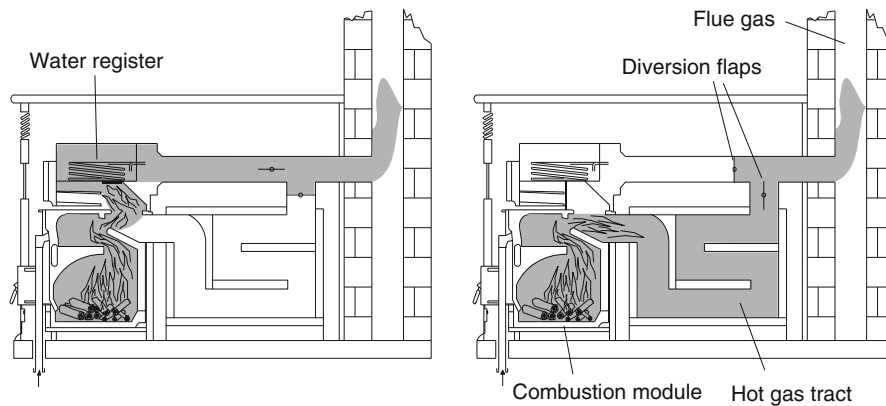
Enhanced masonry stoves, fireplaces, and chimney stoves. The concept of using water as a medium for the transfer of thermal energy for heating purposes does predominate in the case of central heating stoves. However, special designs incorporating the transfer of heat to adjacent rooms (up to a maximum of approximately four rooms) for heating purposes are more commonly found in the case of enhanced masonry heaters and chimney stoves (Fig. 9). This is accomplished either by means of the partly fan-assisted discharge of hot air (from fresh air, mixed air or circulating air supplies) or by way of circulating hot air in a closed circuit system. The latter is also referred to as the hypocaust system, where the circulating hot air acts as the medium for heat transfer. Air is heated up at the surface of the heating insert's heat exchanger. This hot air is then channeled to one or more hot air canals, through the appropriate adjustment of flaps installed in the system, ultimately reaching the heating surfaces in the relevant rooms. These heating surfaces will be finished in the form of special hypocaust tiles, or as ceramic surfaces, natural stone, or brickwork with plaster and provide the medium for the thermal radiation process. Due to the high level of storage mass, this release of thermal energy can happen slowly and evenly over an extended period. Gravity and buoyancy effects generally maintain circulation in the system.



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 9
Working principle of a hypocaust system with masonry stove insert [18] (From Brunner GmbH, Eggenfelden)

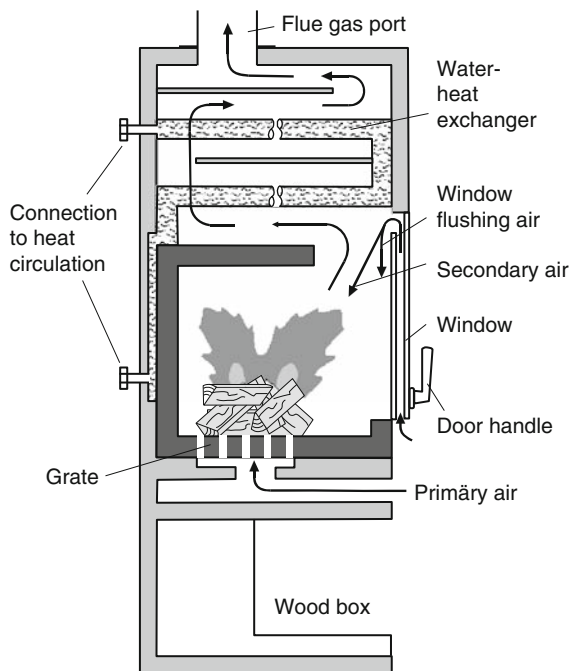
Masonry heaters, fireplaces, and even chimney stoves can also be utilized for the supply of hot water and are referred to in this context as tiled-stove-heating boilers, fireplace boilers or (water) circulating chimney stoves. Special water-heat exchange adaptors ("water registers" or "water jackets") can be opened up for the circulation of hot flue gases through appropriate adjustment of the diversion flaps, as soon as the furnace has reached operating temperature. This is to release part of the thermal energy generated to the liquid medium of the heat exchanger. Heating water is heated up by this process. This change in operating mode for a masonry stove illustrates Fig. 10. The structural design for a water circulating chimney stove is illustrated in Fig. 11.

For chimney stoves, the heat exchanger can also be installed in the closed cycle of a hot air circulation system. The use of heat buffer storages is advisable, in any event. Masonry heater, chimney stove, or fireplace furnace systems with heat exchangers are used up to a rated thermal energy output of around 20 kW.



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 10

Masonry stove with water heat exchanger; (left) additional supply of thermal energy for the heating system, (right) supply of space heating for the location where the unit is installed [18] (From Brunner GmbH, Eggenfelden)



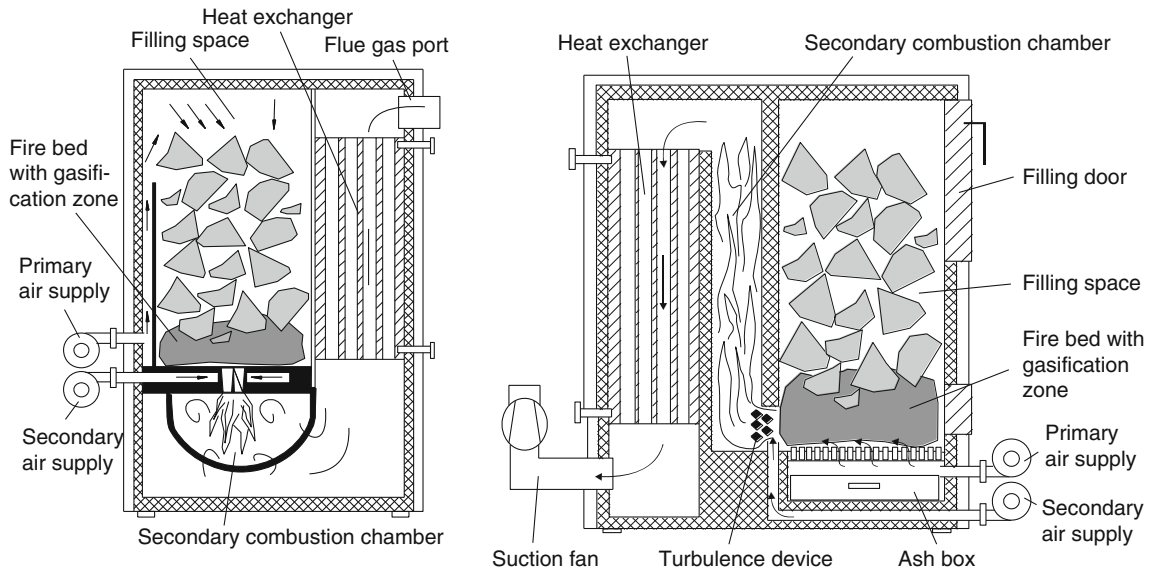
Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 11

Chimney stove with water heat exchanger [18]

Pellet stoves with water jackets. Since the automatic charging with fuel supplies does allow for a relative wide range in the performance of furnaces (approximately 30% up to 100% of rated thermal power

output) the emission of thermal energy from pellet stoves can be particularly well adjusted to the actual demand for heating in residential buildings. This advantage comes to bear especially in the case of systems using water heat exchangers for the heating up of industrial water and water for central heating systems. Additionally, these types of furnaces are increasingly used as a primary source of heating in buildings with low energy design, in combination with other sources of renewable energy (e.g., solar heat) or fossil fuels. In these cases, between 50% and 85% of discharged thermal energy can be generated through water heat exchangers – and at the same time nobody has to miss a clearly visible, flickering flame from the fireplace in the living area.

Central Heating Boilers Other than in the case of stand-alone furnaces or enhanced stoves, central heating boiler are designed to avoid the loss of heat to the surrounding space, since the place of installation will ordinarily not be in a room which needs to be heated and the boiler is unlikely to be needed for cooking purposes. Central heating boilers should therefore be fitted with water heat exchangers (and in exceptional cases with an air heat exchanger) (Fig. 12). Furthermore, they should be connected to a hot water central heating circuit or air circulation system through which the transfer of heat to the heating surfaces in the relevant rooms can be regulated. Surface thermal



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 12

Log wood boiler with vertical downdraft combustion (*left*) and lateral downdraft combustion (*right*) [18]

radiation emitted by such units has to be considered as operational losses and should be minimized through the installation of suitable lining and appropriate thermal insulation measures.

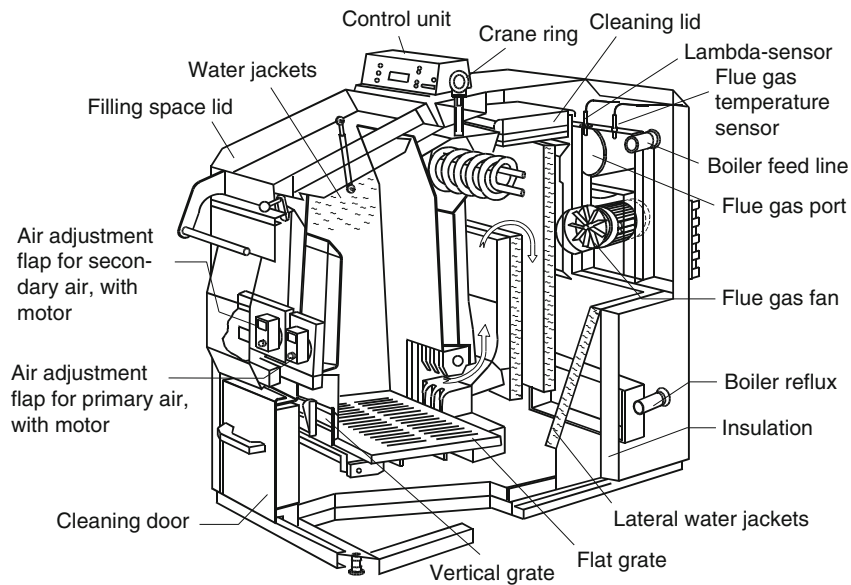
The combustion system used almost exclusively today for hand-charged central heating boilers is based on the downdraft combustion principle (so-called lateral and vertical downdraft furnaces, see Fig. 2) [22]. The filling space is usually loaded with log wood or, less common, with chopped firewood. At a standard thermal energy output rating of 20 to approximately 40 kW, the typical supply of fuel would measure around 30–50 kg in weight per charge. An example of the design for a log wood central heating boiler is shown in Fig. 13.

Combustion air is supplied to the system by way of suction or (less common) pressure blowers, so that the plant can be operated at either high-pressure or low-pressure conditions in the combustion chamber. Boilers working exclusively according to the natural draft principle are less common today. Systems using a blower offer the advantage that the boiler can be operated largely independent of the surrounding conditions (i.e., draft conditions in the chimney). Additionally, a potentially considerable loss in pressure inside the combustion chamber can furthermore be compensated, if appropriate. Such losses in pressure

are inevitable if – in order to arrive at a good mixture of combustion air and combustible gases – correspondingly required turbulences are to be created through diminutions or redirection of air and gas flows.

Within thermostatically controlled systems, the amount of thermal energy produced by the boiler is adjusted according to demand and regulated by the water temperature in the boiler (performance control). But flue gas-based systems for the control of combustion air are being used increasingly. Here, the status of flue gases is monitored with the aid of sensors, in order to provide corresponding control variables for adjusting the air supply (e.g., excess air indicators, CO and C_nH_m). This type of flue gas-controlled combustion air management does also lead to improvements in overall operating efficiency [11, 23], so that log wood-fueled boilers can reach efficiency levels in excess of 90% (in some instances) already today.

Through the use of firewood as a fuel, boilers can be operated under partial load conditions up to 50%. However, the installation of a hot water buffer would also be advisable, in this instance, in order to compensate for any potential fluctuations in the demand and supply of thermal energy. Log wood-fueled boilers are occasionally also combined with automatically charged precombustion systems, where the boiler takes over the



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 13

Example of a log wood central heating boiler working on the basis of the of lateral downdraft combustion principle – charged from the top [14] (From HDG Bavaria Kessel- u. Apparatebau GmbH)

function of secondary combustion and acts as a heat exchanger (section “Wood Chip Furnaces”).

Hand-charged log wood-burning boilers are predominantly used at ratings up to approximately 50 kW. Their performance spectrum, however, ranges from 10 kW for small-scale domestic boilers (exclusively charged with firewood) up to approximately 250 kW for plants which are commercially used in wood processing industries for the combustion of larger pieces of waste wood from industrial production. Plants with a capacity of up to 800 kW are less common, although the principle of downward combustion is also used in these types of installation. In furnaces operating at such high rates of capacity, it is advisable to make use of mechanical aids for the charging of the system (e.g., push carts and/or small tractors).

In order to reduce the comparatively high level of effort and labor involved in the preparation of firewood, adapted boilers for the use of “one-meter-logs” and rolls are available on the market (above 45 kW nominal heat output). This leads to a reduction of the effort required for charging of the furnace and preparation of the wood fuel.

Some firewood-burning boilers can additionally also be operated using heating oil or gas. If an

appropriate burner has to be hinged or swung in front of the wood filling door, the system is referred to as a “conversion combustion boiler.” If the switch in fuel can be arranged without conversion of the system, it is referred to as a “convertible combustion boiler” [6]. A special version of the convertible combustion boiler is the “dual combustion boiler,” which has two furnace systems, completely separated from one another. These derivative systems for the combined use of wood and fossil fuels are rarely found today, due to stringent emission controls and since a further optimization for different types of fuel is not really possible any longer. Firewood-charged furnaces, however, with a swivel or hook-up wood pellet burner allowing for temporary automatic operation, are becoming increasingly popular; and the ease of use, especially during transitional periods (due to automatic ignition) or during extended periods of absence (by the user), has been increased considerably.

Integration into Residential Energy Systems In order to achieve a high degree of combustion efficiency, hand-charged solid fuel burning furnaces should be operated at maximum load levels in relation to the installed rated thermal energy capacity. Actual utilization

of maximum capacity, however, will be required for a very limited number of heating days only, throughout the course of the year. This is the reason why special measures are needed to ensure an economically and technically efficient integration of the system into the overall structure of energy demand, essentially covering the following aspects:

- Selection of a heating system allowing sufficient flexibility in the adjustment to respective load requirements (“load variation”)
- Incorporation of a heat storage device (“heat buffer storage”)
- Use of the wood-burning furnace in combination with other sources for the generation of thermal energy (e.g., solar energy, or even in combination with oil and gas-fired systems, using the biomass-fueled boiler to cover base load demand)

The corresponding options are discussed in more detail below.

Load adjustment. Automatically charged wood-burning furnaces and modern firewood boilers are usually available with controls allowing for the automatic adjustment of the amount of thermal energy emitted (i.e., output controls). The technically feasible nominal load range for firewood-charged boilers (at 50–100% of rated thermal energy output) is considerably smaller than that for automatically charged furnace systems (approximately 25–100%). Nevertheless, load reductions should lie significantly above the stated minimum values to prevent increased airborne emissions. These types of load variable furnaces are generally fitted with a pressure or suction fan adjusted by stepwise or infinitely variable control. The performance of systems operating exclusively on the basis of natural draft, however, can usually not be regulated and they should therefore generally be operated at full load. Other than with partial load systems, considerably larger volumes of surplus heat have to be stored in this case on an interim basis.

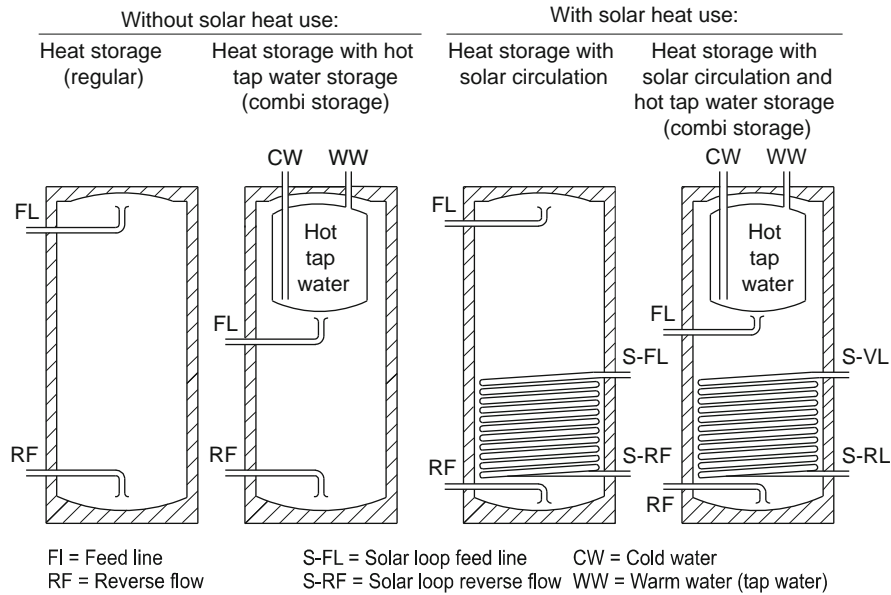
Heat storage. As soon as the demand for heat drops below the minimum possible level of output achievable in continuous operating mode (“lowest possible output of heat”), the furnace has to be switched off automatically through the interruption of the air and/or fuel supply system. Surplus thermal energy can alternatively be fed into a heat storage tank (“buffer

storage”) since water temperatures in the boiler would otherwise continue to rise until the safety system of the boiler is activated.

Commonly used heat storage systems are typically steel containers (with thermal insulation) through which the heat transfer medium is circulated during the loading and unloading process. The feed-in system in the upper part of the heat storage device is usually designed to avoid the development of turbulences, in order to ensure that the formation of temperature layers can take place evenly and uninterrupted. This is achieved, for example, through the use of parallel feed lines with deflector baffles (in the case of vertical installation). Another option is a feed-in flow against the flat inside top of the storage tank (lateral connection, Fig. 14). A particularly distinct formation of temperature layers is achieved in so-called layer storage systems, where the reverse flow of heating water is fed back into the system, by way of an integrated uptake, providing for laminar flow back into the different temperature zones. High feed-in temperatures at the boiler favor the formation of temperature layers and increase storage capacity. For the extraction of stored heat, the flow direction is reversed or separate discharge or reverse flow lines are installed.

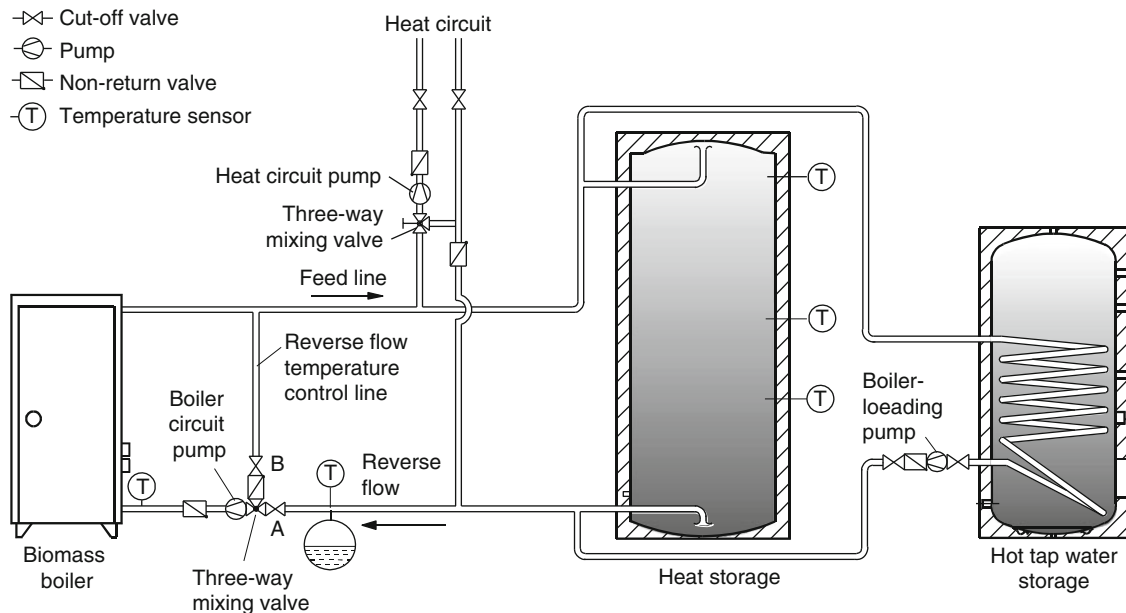
Different types of storage systems are available depending on whether the heating up of industrial water takes place separately or is integrated into the heat storage system and whether it is intended to serve multiple functions, including the feed-in of solar heat (Fig. 14). In the case of a combined system (i.e., storage with integrated industrial water supply), the effective storage capacity for the heat circuit is reduced by the amount of industrial water feed into the system. Heat storage systems are also available in the form of component parts (i.e., disassembled) for subsequent on-site assembly and installation in inaccessible areas (e.g., basements).

In connection with the hydraulic integration of heat storage into the domestic energy supply system, particular attention should be paid to a properly functioning and well-tuned alignment between the biomass furnace, buffer storage and heat distribution system, as heat losses can otherwise quickly run up to 10–20% of the required available thermal energy. An example of a proper system is illustrated in Fig. 15. During the heating up process, the feed line is “short-circuited”



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 14

Different types of thermal energy storage systems [14]



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 15

Example of a hydraulic connection system for the storage of thermal energy in a wood-burning heating system [18]

with the reverse flow (valve B open, valve A closed) in order to reach the required operating temperature (usually around 60°C at the boiler's reverse flow) as quickly as possible ("increased reverse flow"). As soon

as valve A is opened up, hot water can flow into the heat circuit and the boiler. If there is no or only very low demand for energy, charging of the storage system commences. For this purpose, the heat circuit pump

reduces the flow in such a way, that the surplus volume delivered by the boiler circuit pump is directed into the heat storage system. As soon as the delivery of heat from the boiler is interrupted (e.g., drop in flue gas temperature to below 60°C) both valves close automatically (valves A and B in Fig. 15). Since the boiler circuit pump is now switched off, the heat circuit pump can reverse the flow direction inside the storage system and now extract the heat from the upper section of the storage tank.

The volume of storage capacity required is determined by several factors, including the following:

- Capacity range (variable load or boiler operating exclusively at full load)
- Volume of fuel filling space
- Rated thermal energy output value
- Temperature variations in the buffer system (feed flow/reverse flow)
- Demands in terms of operating comfort/ease of use

Furnaces, which can only be operated at their full thermal energy output rating, require larger storage capacities than variable load furnaces, where the amount of surplus heat will be lower because of automatic heat output adjustments. Larger storage capacities, however, are also required if the system (downdraft combustion) has a comparatively large fuel filling space (charging chamber) and correspondingly high levels of heat energy are produced with each single charge.

In order to simplify the calculation of storage capacity requirements, the rated thermal energy output values can also be taken into account, in addition to the size of the charging duct. Storage capacities of at least around 55 l/kW installed furnace output rating are recommended for hand-charged log wood-burning boilers; the target value to be aimed at lies at around 100 l/kW installed [14]. The same applies for load-adjusted firewood-charged furnaces (partial load operation) which should also be operated in or close to the upper range of their capacity to achieve optimum operating performance at the lowest possible level of air pollutant emissions and the highest possible level of operating efficiency.

The heat storage capacity – and correspondingly the volume of storage required – also depends on the effective difference in buffer and heating circuit feed-in temperatures. Discharge from the heat storage system

consequently terminates as soon as the discharge temperature drops below the heating circuit feed-in temperature. Temperature differences arising between the storage (at maximum load) and the heating circuit feed-in range from 25 to 50 K, depending on the design of the heating system. The available capacity of heat storage therefore depends on the heating circuit feed-in temperature, and consequently on the heating system installed. For low-temperature heating systems (e.g., floor or wall heating system), there will consequently be more useable heat available in the buffer system, than would otherwise be the case in conventional radiator systems [14].

Large storage capacities additionally increase operating comfort since fewer start-ups of the system will be required, especially during periods of seasonal transition. Buffering, however, inevitably results in greater heat losses occurring and thus does have an impact on the average annual performance of the overall system. Storage systems should therefore be preferably installed in heated spaces inside the building and/or be equipped with effective thermal insulation.

Combined systems of heat supply. Wood-burning furnace systems, generally speaking, do show relative high levels of emission and low grades of efficiency during summer periods, when they are predominantly used for heating up of industrial water supplies. Alternative solutions in this context are available, for example, by way of a combination with solar systems. Then the use of the biomass boiler may not be necessary at all during the summer and to some extent also during periods of seasonal transition. In the event of such a combined biomass–solar energy system being used, attention must be paid, through the installation of appropriate technical controls and/or monitoring by the user. The biomass-fueled part of the system should not block off storage capacity required by the solar system, if the same heat storage is to be used by both systems. Appropriate intelligent technical control systems, which would also be able to take into account relevant weather forecast, are currently under development.

In providing for peak load demands, especially in the case of larger capacities, it may be advantageous to scale down the biomass-fueled part of the system. This is in order to allow for a substantial reduction in investment costs on the one hand and for a

considerable extension of the period of time during which the biomass boiler can be operated at full load on the other hand. Additionally required supplies to cover peak load demands can then be met, either by means of a cost-efficient oil- or gas-fired boiler (possibly also by way of a boiler integrated into the buffer system), or through the installation of an electric heating rod in the heat storage system.

Automatically Charged Wood Furnaces

The demand for efficient and automated operational processes, combined with a simultaneous increase in the output of thermal energy, has led to the development of automatically charged furnace systems for solid biofuels. The basic differences and technical advantages, compared to hand-charged furnaces, are discussed in section “[Differences between Manually and Automatically Charged Furnaces](#).” Different system technologies are introduced in the following sections.

Automatically charged furnaces are categorized by way of reference to the relative speed of flow of fuel particles and air supply as fixed-bed, circulating bed, and entrained flow combustion systems [19]. However, only fixed-bed furnaces are generally considered suitable for domestic heating systems. According to their respective systems of fuel supply, furnaces can be separated into the following three basic categories: underfed burners, horizontally fed burners, and burners with drop-down fuel supply systems (Fig. 16).



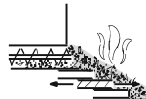
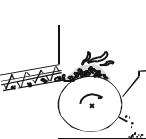
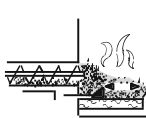
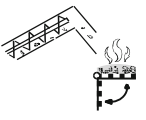
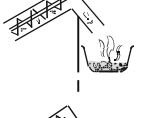
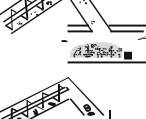

In the case of underfed burner systems, the fuel is supplied to the burner cup (retort) from underneath by means of a feeding screw. Part of the combustion air is injected in form of primary air supply into the retort where drying, pyrolytic decomposition, and gasification of the fuel take place. In order to ensure complete oxidation of the combustible gases formed during these processes, secondary air supply is mixed with the combustible gas prior to entering the secondary combustion chamber. The hot gases subsequently transfer their thermal energy to the heat exchanger. Then they are ultimately released into the atmosphere as flue gas via the chimney system. Fuels to be used in these types of underfed furnaces are low-ash, fine-grade wood chip with a moisture content of 5–35%. Since comparatively high fire bed temperatures are usually reached in this process, this particular form of combustion process is

not really suitable for the use of wood bark or straw fuels. The principle of underfed combustion is employed in the majority of small-scale furnace systems designed for the use of wood pellets.

In horizontally fed burner systems, the fuel is charged sideways into the combustion chamber, which may be equipped with or without a grate (Fig. 16). Small-size wood chip fuel supplies (of relative consistent calibration) are usually charged through a conveyor screw system. Coarse and unevenly formed fuels, such as shredded and/or non-sifted wood or wood bark, either require robust screw feeders or can be charged with the aid of a piston installation. Fixed grate systems are predominantly used for furnaces with lower range capacity (<100 kW). Moving grates systems (e.g., pushing floor or roller grates) are increasingly also used for higher capacity furnaces.

Pushing floor combustion systems without a grate (also known as sliding charge furnaces) are based on an operating principle similar to that of an underfed burner system. If they are fitted with a water-cooled combustion chamber, they are – other than for wood chips and wood pellets – also particularly well suited for high ash producing fuels and other combustion materials liable to the formation of slag (e.g., straw fuels, grains). In the case of lateral downdraft furnaces, part of the combustion air is injected into the system in the form of primary air supply channeled through the grate (if installed) via air nozzles inside the burner cup, or in the case of pushing floor furnaces, via front-end air ducts. Under these circumstances, the primary air supply also acts as a cooling agent for the grate, which in turn reduces the risk of slag deposits and overheating of material occurring during the use of critical fuel substances. Secondary air supply is provided either above the grate and/or fire bed, or prior to entry into the secondary combustion chamber.

High-density wood pellets are typically used in furnaces working with drop down feeding of fuel supplies, as well as in underfed burners and (occasionally) grate-based furnace systems. Drop-down feeding systems are a special design developed specifically for the use of wood pellets. They are therefore not suited for the handling of wood chip. The pellets are fed into the system via a conveyor screw and dropped through a pipe or shaft from above onto the fire bed located either in a removable burner cup, on top of a tilting

Principle	Variant	Type	Scheme	Nominal heat power	Fuels
Underfed burners				> 10 kW (< 2.5 MW)	Wood chips, wood pellets
Horizontally fed burners	Grate furnace	Fixed grate, partly with ash scraper or tilting grate		> 35 kW	Wood chips, wood pellets
		Moving grate		> 15 kW < 60 MW	Wood chips, wood pellets, saw dust, bark
		Roller grate		> 40 kW > 450 kW	Wood chips, wood pellets
	Pushing floor furnace			> 25 kW < 800 kW	Wood chips, wood pellets (>15 kW) herbaceous fuels, grain (with water cooling)
Burners with drop down feeding	With grate	Tilting grate burner		> 15 kW < 30 kW	Wood pellets, precision wood chips
		Cup burner		> 6 kW < 30 kW	Wood pellets
	Without grate	Tunnel burner		> 10 kW	Wood pellets
		Downdraft burner		> 14 kW < 60 kW	Wood pellets, wood logs, wood chips (> 20 kW)

Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 16
 Illustration of operating systems for fixed-bed furnaces – according to feeding systems used [14]

grate, or inside a tunnel (Fig. 16). This is where primary and secondary air is injected from underneath or side-ways through appropriate nozzles (perforations) arranged in the shape of a ring. Depending on their design, furnaces not using a grate can be separated into

cup burners, tunnel burners, and vertical downdraft burners. In addition, there are a variety of other special designs available on the market which can, however, generally be traced back to one of the systems described above.

In horizontally fed furnaces fitted with a grate, the pushing floor is the most commonly used system, although roller grates are sometimes also found. A distinction can furthermore be made between horizontal and tilted grates. More detailed information concerning these different combustion systems (including air supply, feeding of fuel, ash removal, starting controls, and circulation of gas) and the integration of the relevant combustion chambers into the overall furnace systems, in particular, is presented in the following sections and illustrated with selected examples.

Pellet Furnaces A number of special combustion systems do exist for automatically charged pellet-burning furnaces, taking advantage of the fact that pellets can be simply apportioned into the furnace at high energy density. Two of these systems are reviewed in more detail – drop-down feeding with cup burner and drop-down feeding with tilting grate. Additionally, the fuel supply system is explained.

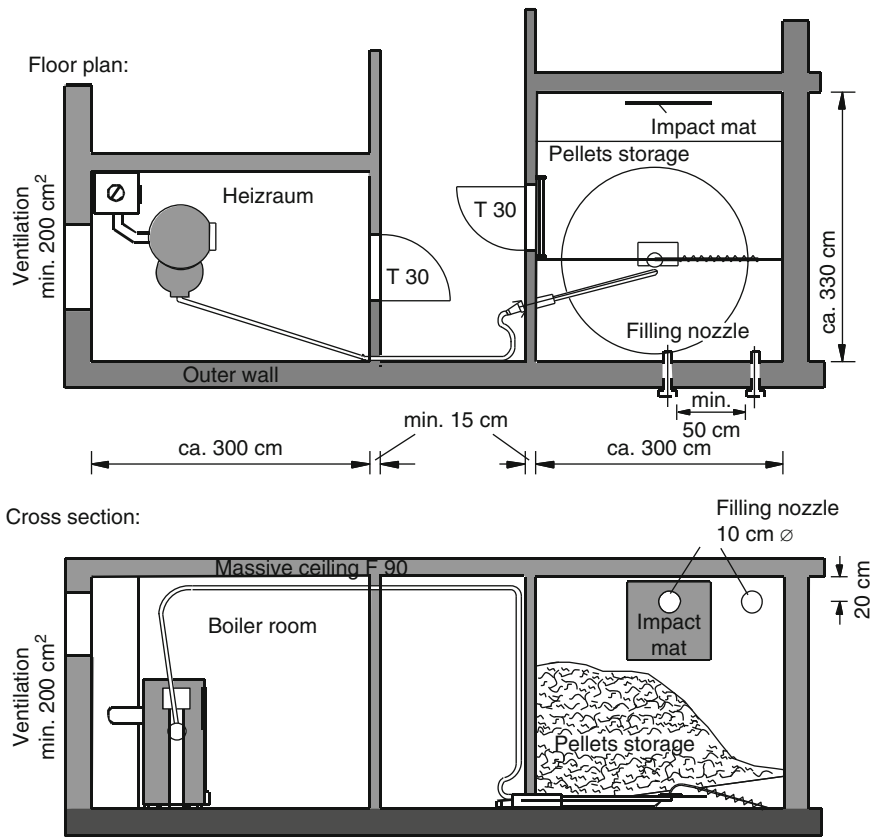
The charging of pellet-fueled furnaces can generally be arranged following the same principles and installation alternatives available for wood chip burning systems (section “[Wood Chip Furnaces](#)”) whereby, here as well, the more cost-effective solutions are available in the form of inclined floor systems with feeding screws or suction fans.

Pellet boilers are frequently used in combination with interim fuel storage containers (often available in the form of compact systems). In these cases, a fill-level indicator is installed potentially also be able to automatically trigger the recharging process. In contrast to wood chip burning systems, even winding or contorted paths of fuel supply from storage to the actual furnace can be accommodated, since pellets are suitable even for transportation by screw conveyors without axle or pneumatic feeding systems (airflow supported conveyance systems). This provides for considerably more flexibility in the utilization of available space. An example for this type of fuel storage connection by means of an airflow-supported conveyance system is illustrated in [Fig. 17](#). Care needs to be taken, that the space where pellets are stored is served by sufficient passive ventilation, as a minimum requirement.

Drop-down feeding with cup burner. With the introduction of standardized wood pellets, the range of

designs for stand-alone furnaces was expanded by the addition of the pellet stove ([Table 1](#)). The advantages of automated charging do come to bear even for the low capacity range of systems used for domestic purposes. By using pellets with consistent fuel characteristics (usually 6 or 8 mm in diameter) and low moisture content (<10%), variations in the combustion process are minimized. This is where pellet stoves and chimney stoves differ from one another, even though pellet stoves may also be fitted with a glass screen for the display of the burning fire. Therefore, they are sometimes also referred to as pellet-chimney stoves.

The fuel is placed into a pellet storage bin located at the back of the stove. This storage is usually filled by hand in the case of most stand-alone furnaces. Due to the high bulk density of wood pellets (ca. 650 kg/m³) comparatively large amounts of fuel can be fed into the system (approximately 20–50 kg), and depending on the operating load status, this supply can last for 1–4 days. Pellets are moved via a conveyor screw into an ascending pipe up to the opening of a dropping shaft through which they are fed into the burner cup ([Fig. 18](#)). During the start-up phase, fuel is ignited in the burner cup either by hand (lighter) or more commonly with an electric ignition (hot air ignition fan or heating element). Details of primary and secondary air supplies are illustrated in [Fig. 19](#). A small amount of additional air supply is usually injected into the system through the dropping shaft in order to reduce the risk of backfire occurrence. As is the case for chimney stoves, additional fresh air (cleaning air) has to be channeled from above along the inside of the glass screen in order to prevent the settlement of dust or soot particles, which might otherwise impair visual appearances. From the perspective of achieving an optimum supply of combustion air, however, such “optical measures” always bring with them certain disadvantages. This is true because the cleansing air cannot be specifically used for secondary air supply purposes and, on the contrary, may potentially even contribute toward a rise in emissions and/or reduction of efficiency by further increasing the amount of excess air in the system. But in general the pellet stove – not least of all due to the fuel’s high degree of homogeneity – commands a leading position in respect of the following two parameters: Emissions of carbon monoxide are well below the values found in the case of other stand-alone



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 17

Example of pellet heating installation with pneumatic feeding system [14] (From ÖkoFen GmbH, Austria)

furnaces. The performance efficiency can reach levels of more than 90% (sections “[Combustion Efficiency](#)” and “[Flue Gas Emissions](#)”).

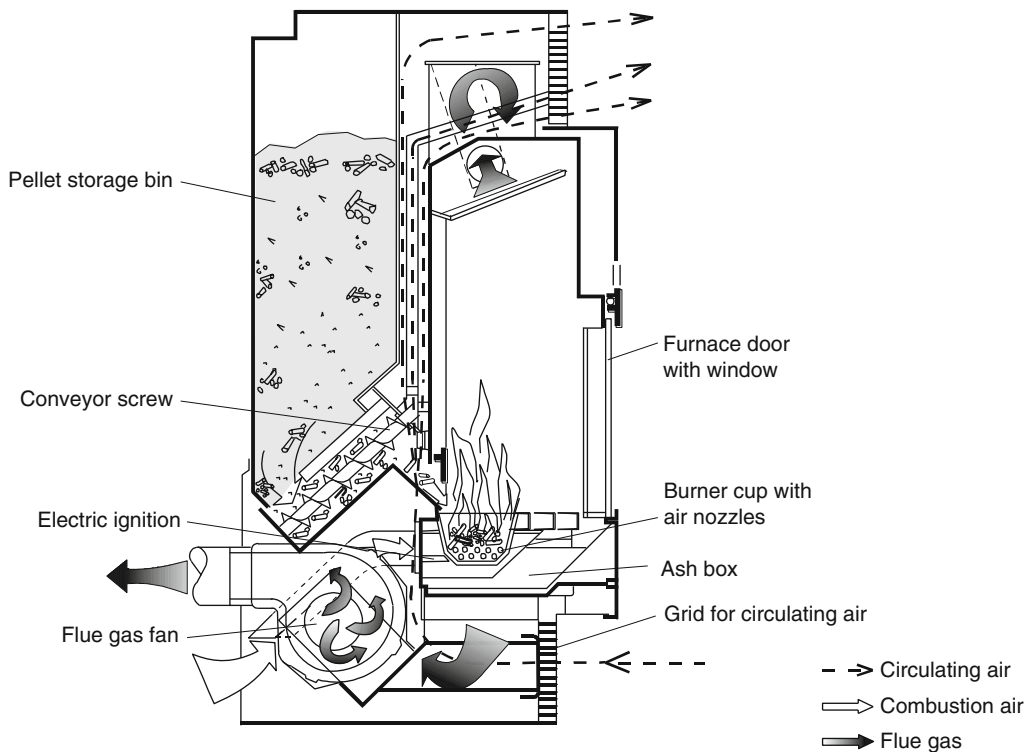
Air is supplied by a low-noise (if possible), graduated or speed-controlled fan system. Air intake is arranged by means of a central inlet manifold, so that pellet stoves with external air supply can largely be operated independently from room air supplies. This operating system is especially relevant for controlled room ventilation systems. Only small amounts of air are still taken from the room of installation (e.g., for cooling of the dropping shaft and the provision of cleansing air).

The flame in the furnace is similar in appearance to that of a gas fire. The release of thermal energy happens partly through radiation, primarily however via convection ducts (Fig. 18). The ashes produced are

removed by hand from inside the burner cup and the ash box.

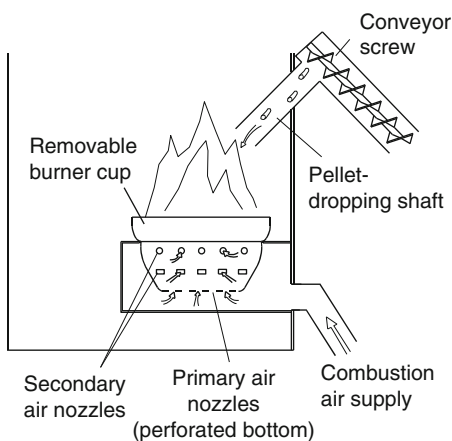
Since pellet stoves are load variable, they are also well suited for continuous operation mode. They are available with capacity ratings up to 10 kW and allow for partial load operations at approximately 30% of rated thermal energy output values, without any significant loss in combustion efficiency.

Details of typical air supply for a cup burner are illustrated in Fig. 19. Primary air is initially channeled into the system through nozzles (perforations) in the bottom of the burner cup, with the aid of a fan (or draft suction), whereas secondary air streams sideways into the burner cup above through a ring-shaped arrangement of air nozzles in the wall of the cup. In other construction designs, secondary air is injected from the side, above the burning fuel or fire bed, through



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 18

Working principle of a pellet stove with drop down feeding and burner cup [19] (From Wodtke GmbH, Tübingen) [18]



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 19

Air supply system for furnaces using burner cups [18]

a ring-shaped arrangement of air nozzles and then mixes with the gases emitted from the fire bed.

Pellet stoves are also available as elements for the refitting of an existing system, similar to the way in

which a natural gas or heating oil burner can be mounted onto an existing heating boiler, thereby allowing for conversion of a furnace system already in place. Such plants can be designed as cup burners or alternatively as tunnel burners, where the pellets continuously trickle from above into a combustion pipe, through which the combustion air passes horizontally, so that the flame of the burner can enter sideways into the combustion chamber at the other end.

The principle of drop-down feeding can also be used for pellet boiler systems. The essential difference is the absence of a display window, making it easier to optimize conditions within the combustion chamber. Combustion principle and air flow system are essentially similar.

Drop-down feeding with tilting grate. In this type of design, pellets are fed into the system via a conveyor screw and dropped from above through a dropping pipe or dropping shaft onto the fire bed positioned on a tilting grate. Then primary and/or secondary air is injected from below or sideways through an appropriate ring-shaped arrangement of air supply nozzles (Fig. 20).

In the case of tilting grate systems, the ashes produced are automatically discharged into the grate ash collector located underneath, as and when needed (e.g., every 16 h). In order to ensure that larger ash deposits are completely removed from the grate, the tilting grate, which is designed in form of a perforated plate, is made to collide with a vertical cleaning plate

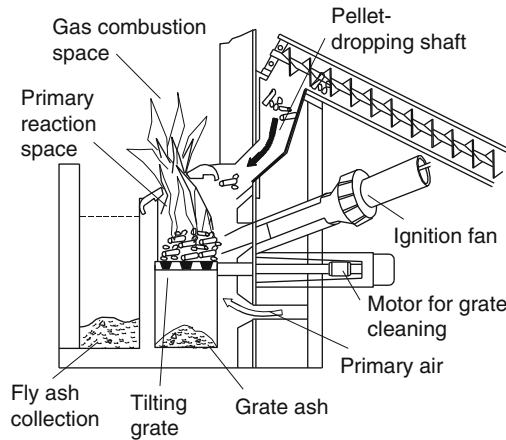
(motor driven) inside the space designated for the collection of grate ashes. This cleaning plate is fitted with spikes arranged in a pattern corresponding to that of the perforations in the tilting grate. Any still glowing embers discharged together with the ashes will burn out in the ash box whilst a new supply of pellets is ignited on the still hot but cleaned grate.

Figure 21 provides a representative example of a pellet boiler fitted with a combustion chamber designed according to the system shown in Fig. 20. This illustration also shows the fuel container with feeding screw, the boiler with the necessary cleaning installations, the suction fan and the systems control unit, together with control panel.

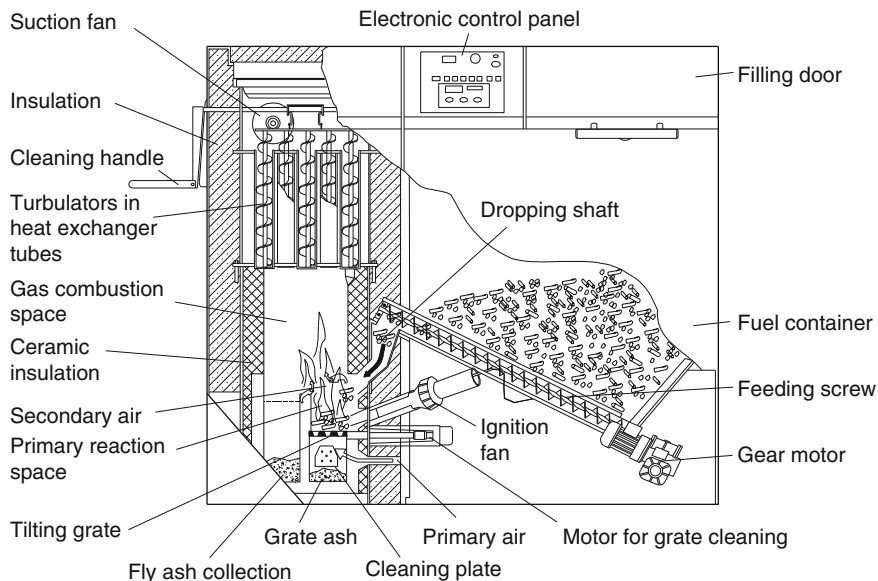
Apart from the combustion systems with dropping shaft fuel supply described above, underfed burners as well as inclined grate furnaces with lateral fuel feeder are used in pellet burning appliances (starting at approximately 10 kW rated thermal energy output).

Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 20

Working principle of a wood pellet furnace with dropping shaft and tilting grate feeding system [18]



Wood Chip Furnaces Underfed and grate based combustion systems, in the lower capacity range, are generally used for wood chips and wood bark in furnace systems of varying design, which are described in



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 21

Example of a 15 kW pellet boiler with tilting grate and fuel container [14, 18] (From Guntamatic Heiztechnik GmbH, Austria)

more detail below. Additionally, the fuel supply is discussed.

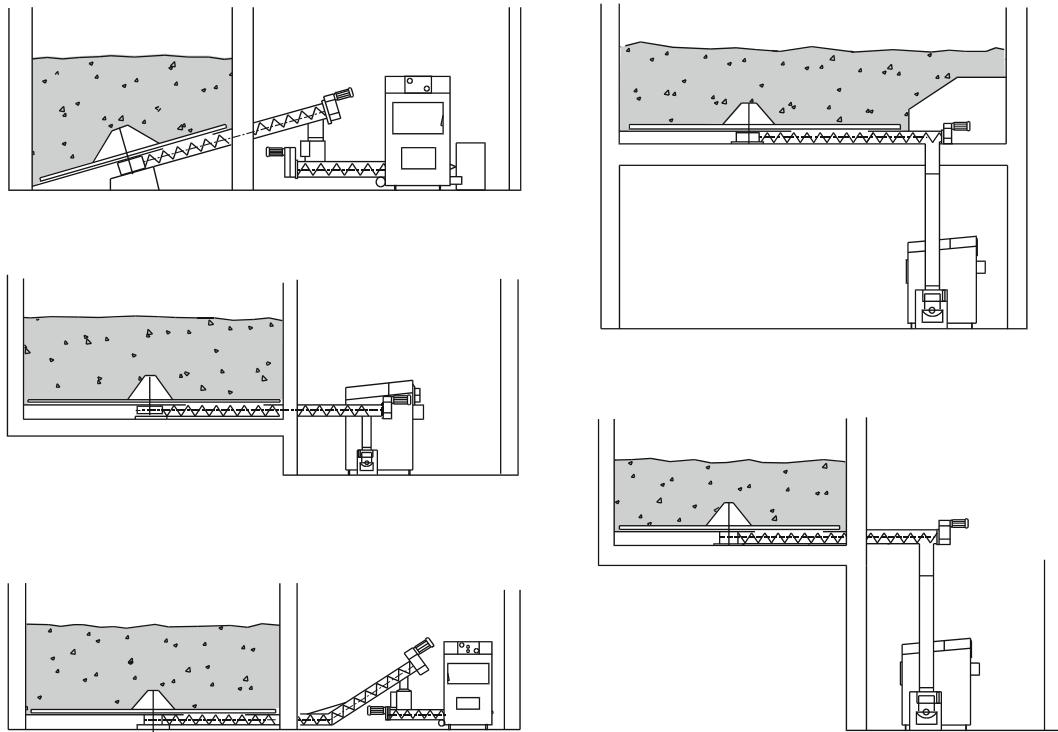
Wood chip furnaces do usually have a fully automated continuous supply system directly connected to area where the fuel is stored. This is typically done with the aid of a double feeder screw installation, with dropping shaft. In these cases, feeder systems are equipped with leaf spring agitators, conical screw-type conveyors or pushing floors.

The discharge level of silos for wood chip arranged either horizontally or as a tilting level, depending on how access for maintenance and repairs to the moving parts is to be organized. A number of installation layouts commonly used for silo substructures, with leaf spring agitator and conveyor screw, are illustrated in Fig. 22. Similar layouts are essentially also possible for the other conveyor systems referred to in section “[Technical Approach](#)”.

Underfed burners. In an underfed furnace system (Fig. 23), the fuel supply is delivered to the combustion

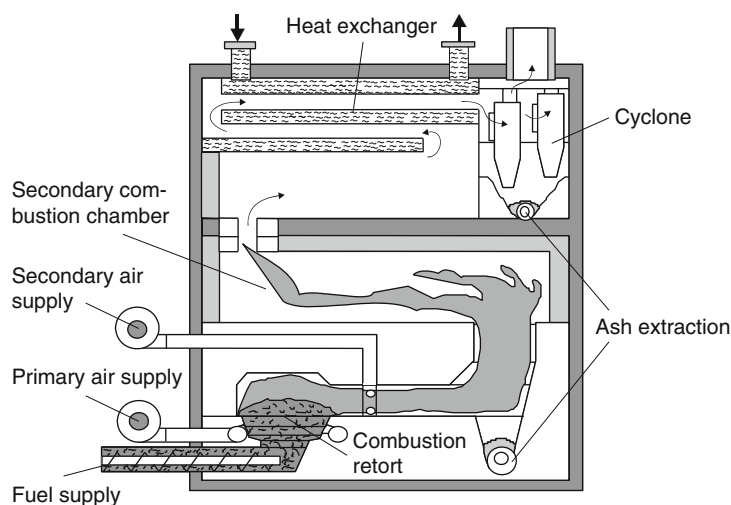
retort from underneath, by means of a screw conveyor. Part of the combustion air is also injected into the fuel (in form of primary air) through the retort, where the drying process, the pyrolytic decomposition, and the gasification of the charcoal take place. To ensure that the combustible gases are completely oxidized, preheated secondary air is usually mixed with the released gases, if possible, prior to entering the heated secondary combustion chamber. The hot gases subsequently flow through the heat exchanger, where they release their thermal energy, frequently followed by a cyclone separator (in large-scale systems), where particle matter emissions are usually removed.

In small-scale underfed furnace systems, wood chips with a moisture content of 5–30% can be used as a fuel; however, fuel supplies and the control of air flow(s) need to be adapted to the relative quality of fuel – particularly with regard to the moisture content of the fuel – in order to prevent technical failure of the system. A plant laid out, for example, for the combustion of wood chip



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 22

Examples of wood chip boilers with leaf spring agitator and screw-type feeding system [14] (From Herz Feuerungstechnik GmbH, Austria)



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 23

Diagram of an underfed burner system [19]

with comparatively high moisture content would reach too high a level of temperature in the combustion chamber if charged with dry wood. This would ultimately result in material fatigue and the formation of slag residue. For the adjustment of the system to changing types of fuel, generally, skilled service personnel are required. Therefore, it is advisable to maintain a consistent fuel quality.

Figure 23 illustrates the operating principle of a furnace system adapted to the specific combustion properties and characteristics of biomass fuel. The zone where the pyrolytic decomposition and gasification takes place in the fire bed is clearly separated from the combustion of the volatile gaseous substances, which takes place in an appropriately sized secondary combustion chamber. The primary air is injected into the fire bed of the combustion retort and regulates the combustion performance. The usually preheated secondary air is blown in at the entry to the secondary combustion chamber and controls the oxidation and thereby the emission of non-combusted substances in the flue gas.

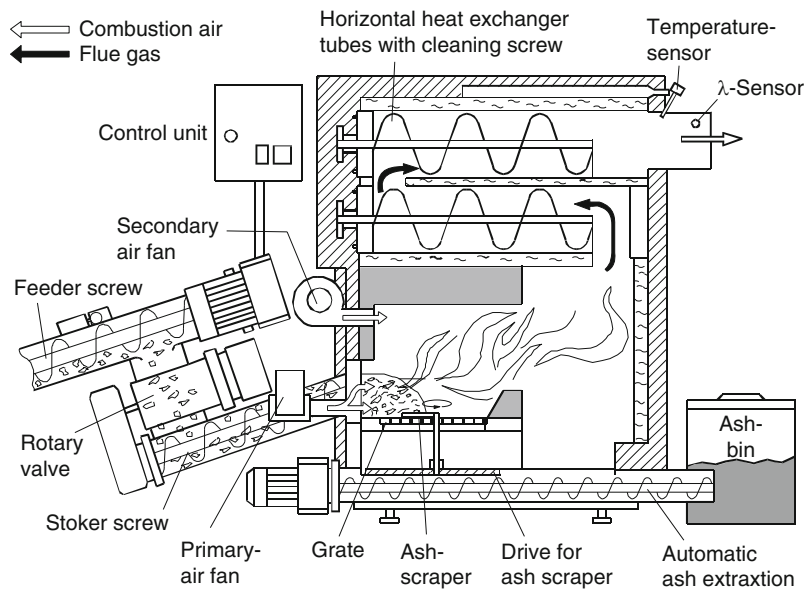
The mixing of secondary air at the entry point of the secondary combustion chamber (Fig. 23) takes place due to the impulse of the air entering into the system. The secondary combustion chamber is additionally configured as a flow pipe. Through this type of design, specifically adapted to reaction technical requirements, optimal rates of reaction can be achieved for a given volume. Through corresponding regulation

of the excess air, the temperature in the secondary combustion chamber can additionally be maintained at the necessary level. This way the stipulations of the “3-T-rule” (section “Combustion Requirements”) are well met.

Underfed burner systems are particularly well suited for low ash fuels with low proportions of under-sized particles, since the feeding by way of a screw conveyor requires fine grain and even consistency (e.g., wood chip). The principle of underfed burner systems is therefore increasingly used for the combustion of wood pellets (e.g., central heating pellet boilers). The combustion of bark or straw fuels on the other hand is not really sensible, given the high level of ashes produced and/or disruptions to the process potentially occurring as a result of the formation of slag.

Horizontally fed burners. Rigid grate systems are predominantly used for horizontally fed burners. An example for this type of burner is shown in Fig. 24. In plants using fuels with a tendency toward the formation of slag, moving grate systems are also used, starting at around 30 kW. In moving grate systems, the fuel steadily travels downward on the inclined grate, driven by continuous forward and backward movement of grate elements.

The pushing floor furnace (also known as “sliding charge furnace”) works similarly to the underfed boiler system. If fitted with a water-cooled burner cup (section “Furnaces for Herbaceous Fuels”), this system is



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 24

Example of a 50 kW wood chip furnace based on the horizontal feed principle with grate and ash scraper [14] (From Heizomat Gerätebau GmbH, Germany)

specifically also suited for the use of fuels with a tendency toward slag formation.

Part of the combustion air is injected in the form of primary air by means of air nozzles in the sidewalls or, as common for moving grate furnaces, at the front of the grate elements. This way the primary air also serves as cooling for the grate, which reduces the risk of slag deposits and material fatigue during when critical fuels are used.

Secondary air is injected above the grate or the fire bed, or prior to entry into the secondary combustion chamber. The ashes produced drop into an ash box or in some systems removed by hand. In the case of high-ash fuels, however, ashes can also be extracted automatically into a larger disposal unit, by way of a conveyor screw system (Fig. 24).

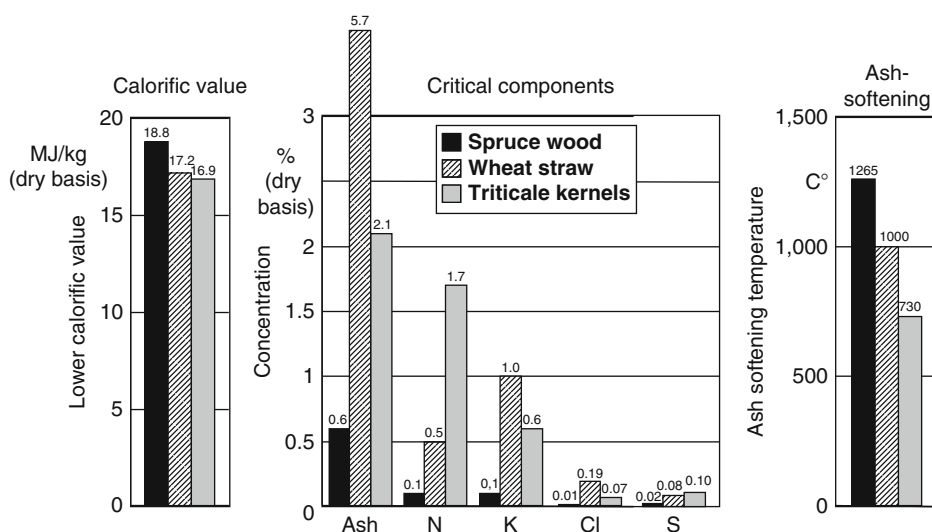
Furnaces for Herbaceous Fuels

Furnaces for (loose fill) straw and cereal fuels (chaff material, pellets, grains) are generally also suited for wood chip and wood pellets; however, the reverse is not the case. Agrofuels such as straw, grass, whole crop cereals, or grains demonstrate numerous disadvantages compared to wood fuels, since they require elaborate

and expensive combustion technologies on the one hand and they make compliance with emission controls currently in force in most countries more difficult on the other hand. These types of fuel are therefore, in practical terms, yet still unimportant, particularly for the segment of small-scale furnace systems.

The disadvantages in combustion properties are numerous. The calorific value is only marginally lower than that for wood; however, the proportion of residual ashes from straw fuels is generally around eight to ten times higher than that for wood fuels. In terms of nitrogen, potassium, and chlorine content straw and grain fuel will again always show significantly higher values than wood (Fig. 25). The aforementioned substances do not only contribute toward the creation of airborne emissions, but also have a negative impact on corrosion and the formation of slag residues in the combustion chamber and on heat exchanger surfaces, which is of particular relevance in the context of furnace system design.

However, the melting properties of the ashes produced are also important, in terms of technical requirements for furnace systems. Here again, ashes from wheat straw with a melting point around 1,000°C are considerably more critical than ashes from the



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 25

Comparative quality characteristics of spruce wood, wheat straw, and triticale kernels (From [13], triticale: wheat and rye hybrid)

combustion of wood (Fig. 25). In the case of cereal kernels, caking of ashes and the formation of deposits inside the system already do occur at even lower temperatures. Straw- and grain-burning furnaces therefore demonstrate different technical characteristics, in terms of ashes and slag separation, temperature control or the pretreatment of fuels.

- Systems designed for relatively low-ash fuels (e.g., underfed burners) are not suitable for the combustion of straw materials. Retort furnaces equipped with ash scrapers or ash pushers, as well as certain grate furnace systems, can be used for a broader range of fuels and can therefore (to some extent) also be used for straw and grain fuels. The drawback of the strong tendency toward the formation of slag can be counteracted by lowering of combustion temperatures in the fire bed area (e.g., through cooled grate elements, water-cooled outside surfaces for the combustion chamber). The risk of separate slag particles forming deposits can also be partially reduced through constant movement of the fuel and the ashes (e.g., in pushing grate furnace systems (section “Wood Chip Furnaces”).
- In the case of straw fuel furnaces, special attention must be paid to the resilience of system components against corrosion and wear (particularly in the heat exchange area). This is to prevent significant limitations to the useful life of such plants. Such risks can, for example, be reduced through the use of stainless steel heat exchangers or silicone carbide for the lining of the inside of combustion chambers. However, there is no real long-term experience available so far. The reason for increases in corrosion is often found in the significantly higher levels of chlorine produced by the combustion of aggressive flue gas substances. But the high potassium content as well, which results in corrosion promoting deposits on system components exposed to flue gases, does contribute to corrosion.
- Compliance with emission control thresholds in the combustion of straw materials can often be safeguarded only through the installation of elaborate secondary flue-gas cleaning systems. Conventional cyclones provide close to zero efficiency in the separation of especially small “submicron” particles, which represent the majority of particulate matter emissions. Effective separation is only possible with the aid of filtrating separators (e.g., through the use of metal netting filters, packed bed filters, cartridge systems) or through electrostatic separation (electrostatic precipitators, section “Secondary Flue Gas Treatment”). Such measures, however, still result in an unacceptable increase in costs for the overall system.

In the combustion of straw fuels, a distinction needs to be made between loose fill combustion systems, using a debaler or already loose, chopped, or pellet material, and systems capable of handling whole bales as fuel. These types of systems are introduced below.

Furnaces for Bulk Material In order to solve and control the special problems arising from the combustion of straw fuels two different ways are used: the adjustment of fuels to the combustion technology, or the adaptation of furnace systems to the different types of fuel.

Adjustment of fuels to the combustion system. The process of slag formation can be counteracted through the addition of additives or the creation of special mixtures of biofuels, as the melting properties of ash from the combustion of biomass fuels depend on the specific composition of the ashes. Based on the present state of knowledge, it would appear that the calcium and potassium content of the fuel are the crucial factors. Calcium containing substances, such as caustic lime or pulverized limestone in particular, act to increase the melting point of ash. Since these are noncombustible additives, the amount of ashes to be removed from the furnace will increase by approximately 15–60%, allowing for the usual addition of aggregates accounting for approximately 0.5–2.0% of overall weight. Special equipment is already available on the market for dosage and mixing of these aggregates; and custom-designed solutions are additionally employed.

Adjustment of the combustion system to fuels. The process of slag formation in special straw burning furnace systems can be avoided by two measures often used in combination:

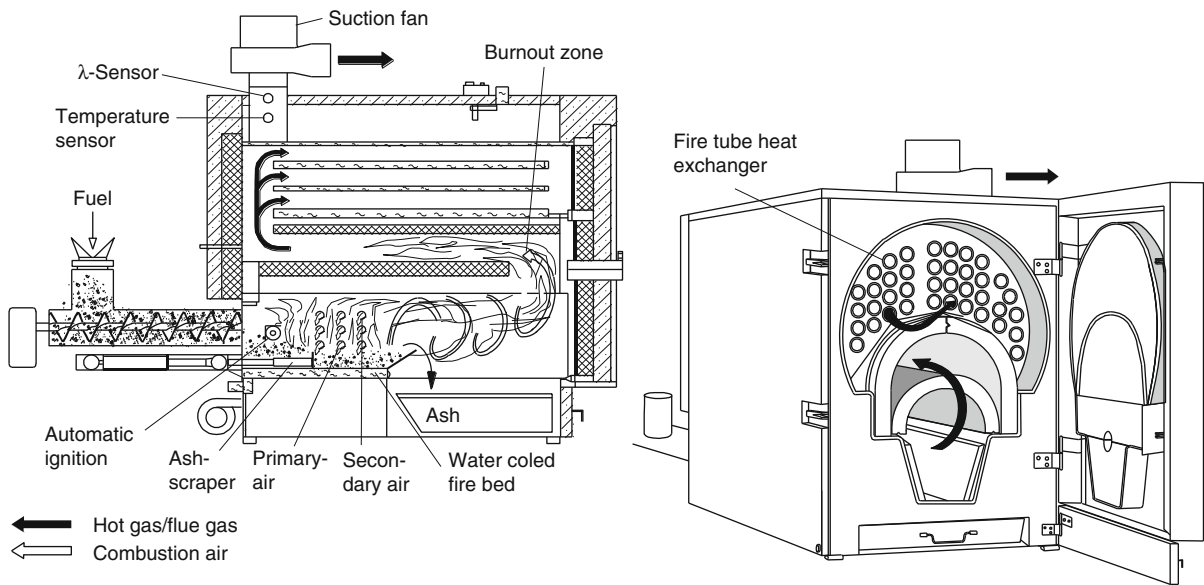
- Limitation of combustion temperature in the fire bed.
- Keeping fuel and ashes permanently in a state of movement.

Inflowing primary air already contributes toward a reduction of temperatures (“cooling”) in the fire bed. However, since the amount of primary air is strictly limited by the requirements for an efficient pyrolytic decomposition and the gasification of the remaining carbon, additional cooling can be achieved through

regulating the circulation of flue gas in the combustion chamber. Reliable cooling, at least for the surface areas in small-scale furnaces, however, can only be achieved through cooling down (water-cooled) the surfaces in the fire bed or combustion chamber (e.g., heat exchangers installed underneath the retort in the combustion chamber). In large-scale systems, this can be realized through the use of water-cooled grate components. However, since the formation of slag deposits – without the addition of aggregates – cannot always be avoided, it is important that the slag produced does not settle and can be easily removed.

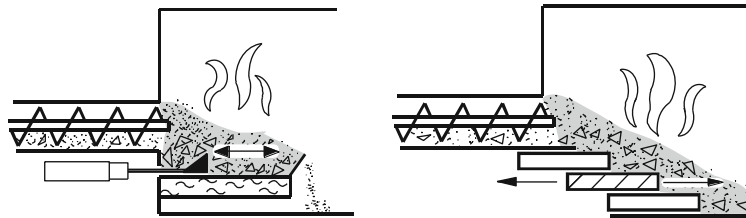
For the removal of large amounts of ashes, an oscillating ash scraper can be used (Fig. 26). Similar to the pushing floor system sometimes used in fuel storage facilities, the scraper has a wedge-shaped profile allowing for the removal of ashes, with the steep edge facing forward into the direction of the ash disposal system; whereas in reverse motion, the scraper passes underneath the resting bed of ashes. Moving grates can also be used as an alternative solution (Fig. 27). This way it can be avoided, at least partially, that individual slag particles start forming deposits in the system. These movements lead to the fuel entering the combustion chamber being leveled out in the fire bed, through the motions performed by the scraper, grate, or ash removal elements, whilst the ashes produced are moved to an ash box located in the back. If it significant amounts of slag settlement on elements of the combustion chamber cannot be safely avoided, serious disruptions in the supply of combustion air may occur, for example, by the clogging of air nozzles. The disadvantages range from severe disruptions to the combustion process and damage being caused to the plant, up to a complete breakdown of the system or excessive pollutant emissions.

In order to avoid such disruptions, furnaces, in order to be suitable for the combustion of straw fuels, do need an efficient automated ash removal system. An added factor is that under unfavorable conditions, pieces of slag produced may grow to a size, which makes the removal by means of a screw conveyor impossible, and which would therefore cause a disruption to operations. The use of additional agitator systems may turn out to be necessary (e.g., worm-shaft type systems with catches). The removal of ashes, especially in systems with ratings significantly above



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 26

Pushing floor burners suitable for straw fuel supplies (here: 49 kW) with water-cooled fire bed (here without automatic ash scraper) [25]



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 27

Pushing floor burners with water cooling system in the fire bed (*left*) and moving grate burners for straw fuels (*right*)

100 kW, is sometimes also arranged directly into a fireproof container, located right underneath the combustion area, which can then be easily replaced.

Furnaces for Whole Bales Furnace systems designed for the combustion of whole bales are typically found in plants with ratings above 100 kW. These are usually continuously charged systems (starting at around 2,000 kW) or intermittently charged (i.e., consecutively fed) smaller furnace systems starting at around 350 kW

frequently found, for example, in Denmark. In the range of rated thermal energy output levels of below 100 kW, such (bale) systems are only used very rarely.

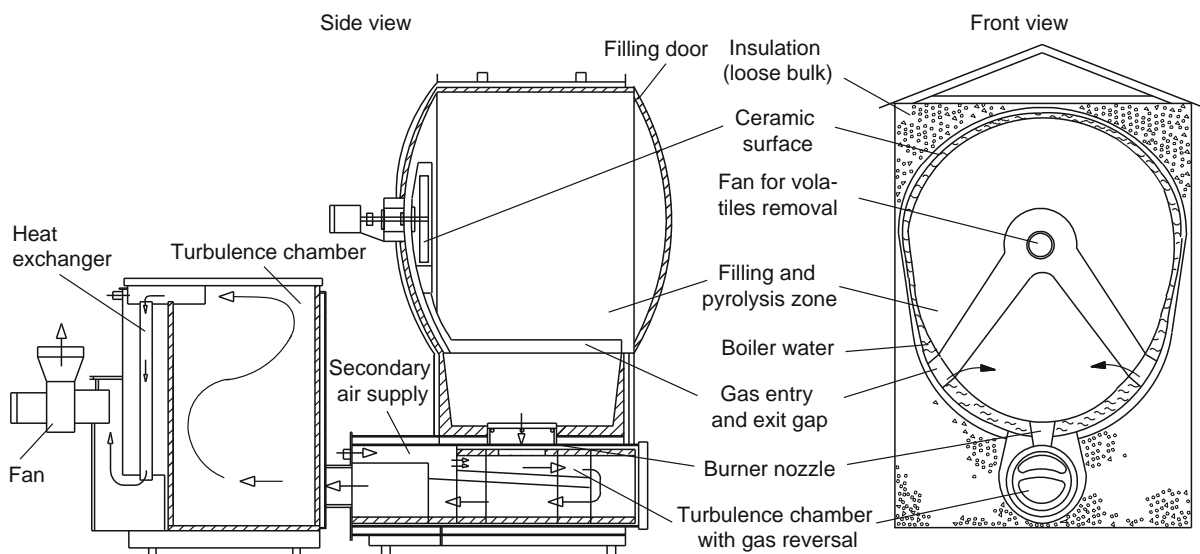
Given the dimensions of bales, commonly in use today, the charging process is handled mechanically; for example, with the aid of front load tractors, whereby in the largest of these plant layouts up to three big bales (round or square bales) can be charged simultaneously into a water-cooled combustion chamber.

In whole bale furnaces – similar to hand-charged systems – fuel is combusted in charges, with the characteristic phases of initial combustion of volatiles and the subsequent combustion of carbon substances. If such plants do operate on the principle of updraft combustion without grate (section “[Principles and Operating Systems](#)”) the intermittent and as such difficult to regulate nature of the combustion process is particularly pronounced. The advantage of this combustion principle however is, that these systems are suitable for a wide range of different sizes and shapes of bales. In various markets (e.g., Germany), these systems are not available due to their high levels of pollutant emission.

Recently, the principle of downdraft combustion is also applied in whole bale furnaces (Fig. 28). This involves the selection and subsequent commitment to one specific size and shape of bale to be used for combustion. The advantage of this combustion principle, however, is that the progress in combustion is considerably more evenly balanced, and therefore easier to regulate and control. Nevertheless, more or less major swings in performance, temperature, excess air, and discharge of pollutants (e.g., carbon monoxide) do frequently occur in this type of plant during the course of combustion. This is a feature that these systems have

in common with hand-charged wood-burning furnaces. That is why whole bale-charged furnaces, if at all possible, should always be operating under full-load conditions (especially smaller systems); generally these systems will require a relatively large volume of heat storage (section “[Integration into Residential Energy Systems](#)”).

The system design for a smaller whole bale furnace system is illustrated in Fig. 28. In order to avoid the formation of slag and ash deposits here again – the same as in the case of loose fill furnaces for straw fuels – the critical factor is the reduction of temperatures in the area where fire bed ashes do occur. Cooling of the fire bed therefore is also provided for in these systems. It is typically arranged through the installation of a water jacket enclosing the combustion chamber. The primary air required for combustion is channeled horizontally through the straw via air vents, together with low-temperature carbonization gases (from pyrolytic decomposition) extracted from the upper combustion chamber, to facilitate the combustion of the bale located in the lower section of the combustion chamber. The secondary air is subsequently supplied to the combustion chamber underneath (turbulence chamber), similar to the design found in hand-charged central heating boiler systems.



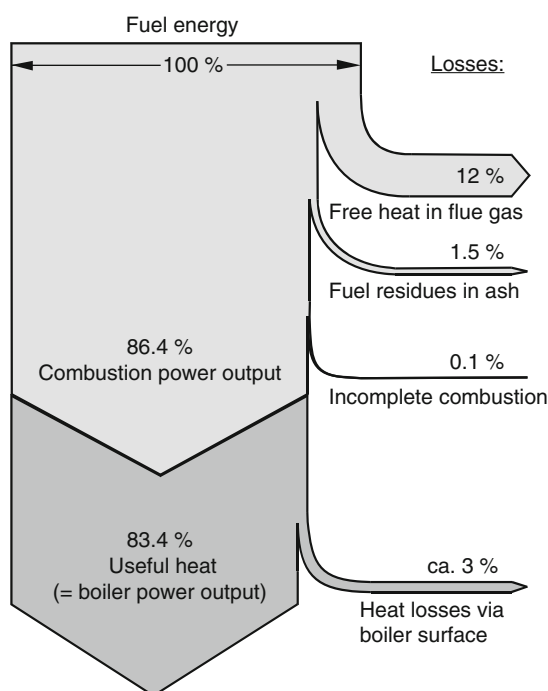
Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 28

Diagram for round bale furnace (145 kW) for straw-type fuels [14] (From Herlt SonnenEnergieSysteme, Germany)

Combustion Efficiency

When evaluating the efficiency of systems, a distinction is made between combustion efficiency and boiler efficiency. In the case of stand-alone furnaces and enhanced stoves, only the combustion efficiency is specified because the major proportion of available thermal energy is released directly into the surrounding space, and not via a heat transfer medium. A specification of both efficiency ratings is possible only in the case of central heating boilers.

The difference between these two efficiency parameters can be illustrated by the typical flow of thermal energy in a small-scale boiler system (Fig. 29). In calculating the combustion efficiency, the losses due to heat released through the discharge of flue gas, combustible residues in the ashes and incomplete combustion are taken into account. With regard to boiler efficiency, losses due to thermal energy released by the surface of the boiler still have to be added, so that the boiler



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 29

Diagram of typical flows of heat generated by a wood chip boiler (50 kW) at rated thermal energy output values [24]

efficiency rating for small systems will generally tend to be approximately 3% lower than the combustion efficiency rating.

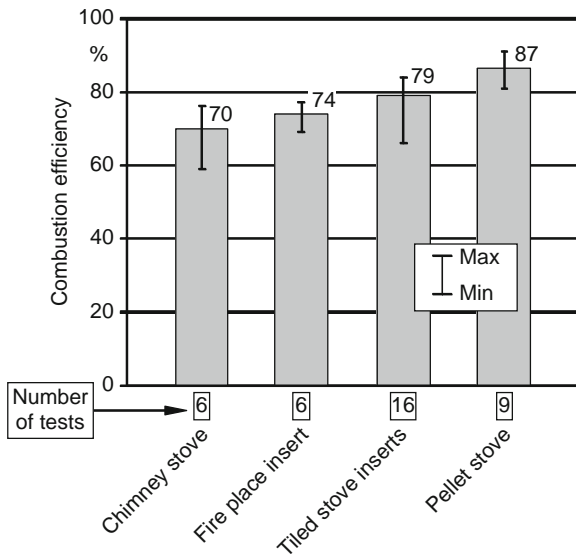
The flow chart (Fig. 29) demonstrates that the flow of flue gas represents by far the largest contributing factor with regard to the loss of thermal energy. Active measures for the improvement of efficiency are therefore usually aimed at the reduction in flue gas temperatures, whereas improvements in the combustion of gas primarily serve to reduce the emission of pollutants.

The potential for the lowering of flue gas temperatures, however, is limited. In chimney systems liable to be affected by the impact of humidity, temperatures below the dew point are to be avoided. This is true to prevent the formation of condensate, which could not only penetrate the chimney itself, but can also lead to permanent damage occurring to the whole structure of the building (discoloration of brickwork, sedimentation) and increased risks of fire (chimney fire). Additionally, a minimum chimney draft has to be maintained for all chimney systems not equipped with a fume extractor, through the safeguarding of sufficient temperature differences between the flue gases and the surrounding environment.

Efficiency of stand-alone furnace systems. For the segment of hand-charged stand-alone furnaces (stoves), combustion efficiency ratings between 70% and 80% can be expected (Fig. 30). The efficiencies for pellet stoves are likely to be considerably above these values at a rating of approximately 87%. These systems are generally comparable to wood-charged central heating boilers (Fig. 31).

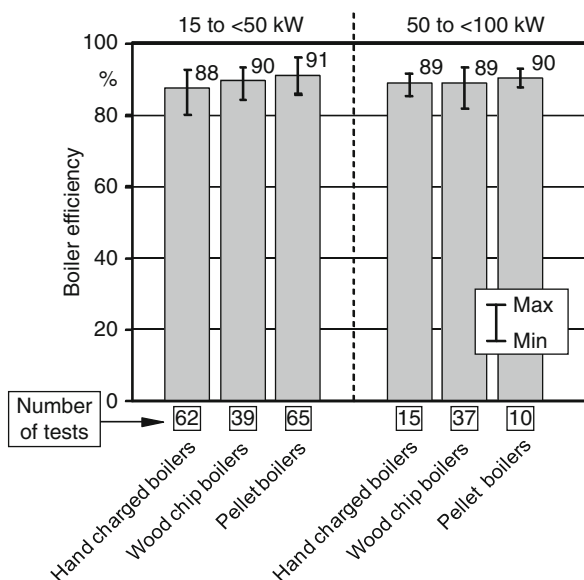
The combustion efficiency values for the different systems shown in Fig. 30 only relate to the actual furnace itself, as flue gas temperatures are always measured at the flue gas connecting pipe of the stove and not the exit point of the chimney. If the system, however, is equipped with a long chimney tract, leading through rooms to be heated, a further cooling down of flue gases is likely to take place. The actual amount of useful heat released would therefore be higher, so that the efficiency rating for the overall system, indeed ought to be set higher.

In type testing performed on furnace test benches today's stand-alone furnaces (stoves) often achieve higher efficiencies, especially since most modern



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 30

Grades of combustion technology-related performance for stand-alone wood-burning furnaces at rated thermal energy output values [12]



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 31

Efficiency rating of central heating wood boilers at rated thermal energy output values; result of 10-year evaluation of tests over the period from 1996 to 2006 [12]

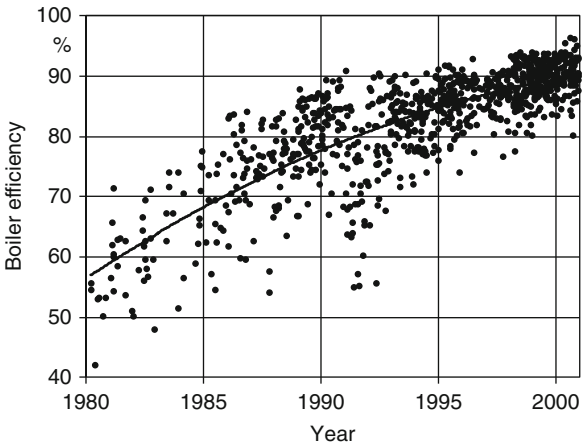
stand-alone furnaces, meanwhile, do have to be able to meet the specific requirements of quality labels (e.g., DIN_{Plus} in Germany). For manually charged stand-alone furnaces it can, nevertheless, be expected that the actual efficiencies achieved in practical day-to-day operations will tend to be somewhat lower than those stated in Fig. 30. Efficient operation of these systems depend to a large degree on the way the system is operated by the user; potential errors in operation (e.g., too high a level of excess air, use of still moist wood fuels, overloading of the combustion chamber, too large or too small pieces of wood) will have a particularly negative impact on performance. These types of errors, however, can generally be avoided if the relevant instructions contained in the operating manual are followed.

The above-mentioned impact of the way in which the system is operated by the user hardly does come to bear in the case of pellet stoves. Since they involve the handling of a uniform standardized fuel material, which additionally can largely also be fed automatically into the system, without user involvement, the efficiency rates shown can also be readily used in practice.

Efficiency of central heating systems. In the case of central heating wood boilers, the combustion efficiency ratings are generally not used as a relevant indicator. Here the boiler efficiency rating is considered, where the performance values are approximately 2–4% lower (Fig. 31). However, almost without exception all values are around a level in excess of 85%; in the case of the most recent boiler designs almost all exceed even the 90% threshold. The simplest way of achieving this result is with pellet central heating boilers, whose ratings tend to be around 2–3% above those for all other types of wood-burning central heating systems. Generally speaking, the variations in efficiency between the different designs and performance categories for any of these systems are rather small.

In the case of the rates of boiler efficiency stated above, the amount of thermal energy released to the surrounding space of the boiler (e.g., radiation) is, by definition, not accounted for as a loss. However, if there is a certain amount of heating required in the space of installation, the overall amount of useful output of heat, from the perspective of the user, is increased. The same applies in respect of the cooling down of flue gases in the chimney tract.

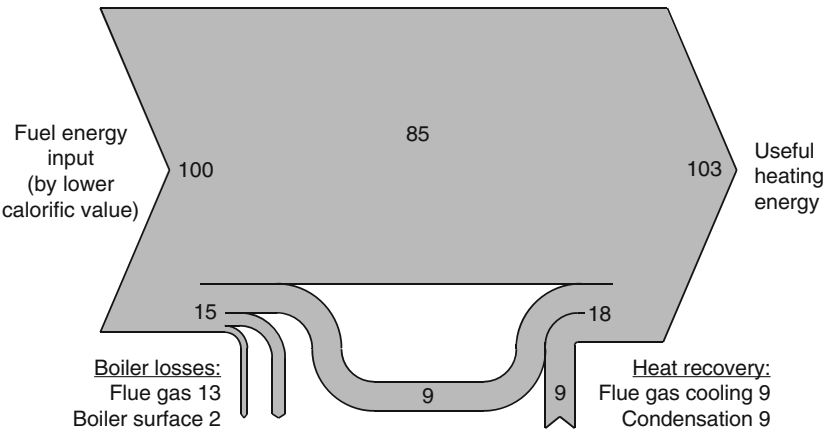
Development of degrees of efficiency. In recent years, further technological developments for wood-burning central heating systems have taken place clearly demonstrated by boiler efficiency ratings. They have improved since the start of the 1980s until the present by approximately 30% (Fig. 32).



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 32
Development of boiler efficiency for hand- and automatically charged wood-burning furnaces at lower capacity ranges since 1980 – results from different boiler-type tests at rated and partial thermal energy output performance [12] (From BLT Wieselburg)

Any significant further increases in rates of efficiency are therefore likely to be achieved only through the introduction of additional condensation heat exchangers. That way flue gases emitted by a wood-burning furnace could be cooled down below the dew point and thermal usage of the latent heat fuel would be increased considerably. This process, which already is standard practice for most natural gas-fired burners (“condensing boiler technology”), could lead to system performance ratings in excess of 100% (based on the lower calorific value H_u , Fig. 33). In the field of biomass fuelling, this effect has so far been used only in the case of larger wood-fired heating plants. But meanwhile this technology has also become available for use in domestic central heating systems. Without any additional consumption of fuel, an increase in performance (and in efficiency) of 18% on average can be achieved. Through the buildup of condensation, particles could be washed out of the flue gas reducing the overall level of air pollutants emitted by the system. In the case of wood fuels, the level of dust separation would reach around 20–40%, depending on the moisture content of the fuel and reverse flow temperatures of the heating cycle [16, 17].

In practical applications of the condensing boiler technology, it will be necessary to find appropriate ways of making use of low-temperature thermal yields (e.g., in low-energy building design with underfloor



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 33
Energy flow diagram for condensation operation. Data given as percentage of total fuel energy input (100%) based on lower calorific value [15]

heating). However, for many users (e.g., old buildings) such conditions do not apply. Opportunities for the economic utilization of the condensing boiler technology are therefore likely to exist primarily in connection with the installation of new heating systems in new buildings, and in respect of pellet boiler systems, where a relative expensive fuel could be saved through an increase in efficiency.

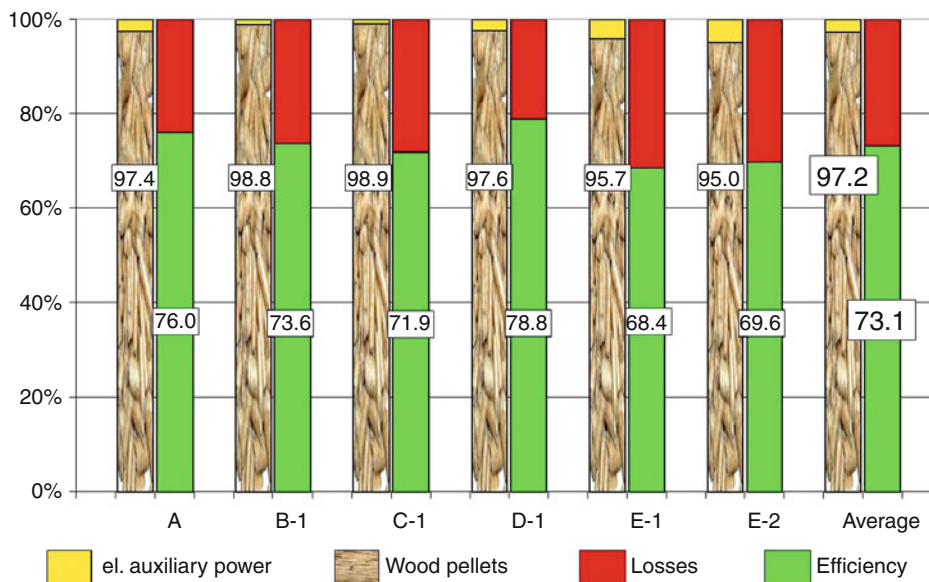
Combustion efficiency versus annual efficiency. The quality of combustion technology, as such, can be quite well defined by reference to its level of combustion or boiler efficiency. But the actual annual operating efficiency of the system is the decisive factor for the user and his annual requirement of fuel supply. This is determined by the user's annual demand for heating in relation to the amount of fuel required for this purpose. Annual operational rates of efficiency for biomass-fueled furnace systems can range from 70% to 85%, depending on the combustion technology, capacity design, supply requirements, size of buffering, and system of controls (Fig. 34). Thus, the optimization of the overall system is essential, also in the case of biomass-fueled furnaces, in order to achieve a high overall efficiency.

Flue Gas Emissions

Below, the emission of pollutants from biomass-fueled furnaces is described depending on the types of design, fuels used, combustion processes, and charging systems. The review is restricted to the limited number of essential pollutants, which are primarily the carbon monoxide components (CO) and particulate matter emissions, as well as emissions of NO_x and volatile organic hydrocarbons. For the latter, controls are not always mandatory for small-scale systems and therefore these parameters are recorded less frequently. Additionally, flue gas treatment technologies are discussed.

Emissions of Stoves

In the case of stand-alone furnace systems (chimney stoves, masonry/tiled stoves and standard masonry heaters, pellet stoves, etc.) the levels of emission are generally not regularly recorded, given the disproportionately high effort that would otherwise be involved. For this reason, the results of type certifications have frequently been used in the evaluation (e.g., from measurements for the quality label). Such type certification procedures, however, are rarely performed under



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 34

Assessment of annual efficiencies of various wood pellet boiler installations in Germany (wood pellets and electrical auxiliary power as energy input) [21]

real-life conditions, so that the gathering of reliable data concerning the typical operating performance of a stand-alone furnace is only possible through the performance of special trial runs, with test results being recorded throughout the whole of the combustion cycle. Such measurements are usually taken from official public sector commissioned studies (e.g. [9, 12]). The results from such studies show, that average emissions of carbon monoxide, in the case of hand-charged stand-alone furnaces, might stand at a level of around 1,500–5,000 mg/Nm³, whereby permanently installed furnaces (e.g., masonry tiled stoves) show the most favorable results. A clear exception to this are pellet stoves, which only show one tenth to one twentieth of the emissions recorded for firewood charged stoves. The advantages of pellet stoves become even more clearly visible in relation to volatile organic carbon compounds, commonly also simply referred to as hydrocarbons. The differences in combustion follow the order in the level of CO emissions.

This does not, however, automatically apply with regard to the overall level of emissions, since, in addition to factors such as complete combustion, other processes also do have an impact on the emission of fine particles. High proportions of soot and tar, high flow speeds, and system internal zones with settlement of dust particles are responsible for different kinds of variations. The marginally higher emission of particle dust by chimney stoves could also be the result of several processes, which might increase emissions, taking place simultaneously. The emission levels of NO_x in contrast, are primarily determined by the nitrogen content of the fuel while the impact of combustion technology is rather insignificant in the case of small-scale systems.

Emissions of Boilers

In the case of wood-charged central heating boilers, a considerably lower level of emissions is generally found compared to the levels reached in hand-charged stand-alone furnaces. This does apply in particular in respect of pollutants such as CO, total organic carbon, and partly also for emissions of particulate matter.

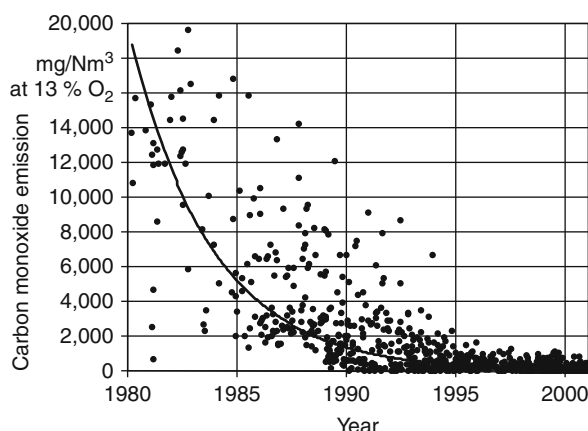
CO emissions. The CO emissions of a firewood-charged boiler are, as a rule, around one tenth of the values recorded for a stove charged with firewood

(Fig. 36), even though both furnaces are charged in the same way. The range of measured values, however, still remains rather broad, which is due to the wide variety of different types of construction designs (natural draft systems, fan-assisted combustion, lambda-controlled systems). Firewood-charged boilers, with flue gas-regulated supply of combustion air, will typically mark the lower end of the spectrum in terms of CO measurements, which will range here on average between 80 and 250 mg/Nm³.

A shift from manual to automatic charging will result in significant improvements in the quality of combustion, which is reflected by the overall levels of CO and total organic carbon emissions; whereby the difference between wood-chipfueled and pellet-fueled systems is, in parts, relatively small. In practice, however, greater advantages can be expected from pellet boilers, since pellets constitute a source of fuel characterized by continuously high combustion efficiency (uniform, standardized type of fuel); whereas in the case of wood chips, significant differences in quality frequently do occur, with clear variations from the kind of fuel used during combustion-related technical testing. Measurements taken in field testing therefore often produce significantly differing results from the average type testing values shown here [26].

By way of reference to the relevant levels of CO emissions, the technological development over recent years can be seen quite clearly, and since the beginning of the 1980s they have contributed toward a clear reduction in the emissions of pollutants. This is supported by the evaluation of the results of the type certifications already referred to above (Fig. 35). Concurrent to these improvements in the efficiency, boiler systems for furnaces have been accomplished (section “Combustion Efficiency”).

Volatile organic carbon compounds. Similar to the developments in CO emissions, a reduction in the emissions of volatile organic carbon compounds (i.e., TOC – total organic carbon or C_nH_m) from larger systems, with higher nominal thermal energy outputs, can be noticed (Fig. 36). The same applies for the load-related performance of furnace systems, that is, the level of CO and TOC emissions (Fig. 36) does increase significantly, as soon as the system is operated at reduced loads (i.e., in partial load mode) or even at minimum thermal output rating.



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 35

Development of CO emissions for hand- and automatically charged wood-burning furnaces at lower capacity ranges since 1980 – results from different boiler-type tests at nominal and partial thermal energy output performance [12] (From BLT Wieselburg, Austria)

Emission of particulate matter. The connection established in terms of efficiency, between levels of CO and TOC (total carbon) emissions and the relative performance and/or operating loads of systems, does not apply in relation to the emission of particulate matter. These emissions are instead determined by other factors, such as movements in the fire bed, the contents of aerosol-producing substances in the fuel and the existence of potential zones of settlement and/or formation of deposits. Wood chip furnaces will tend to develop higher levels in the overall particulate matter emissions, compared to hand-charged firewood boilers, where the fire bed will ordinarily remain undisturbed. This kind of undisturbed fire bed is frequently also found in pellet-fueled systems, if these are designed in the way of drop-down furnaces, where the area of the fire bed is hardly affected by potential mechanical disruptions. Pellets furthermore do represent a comparatively low-ash-forming fuel.

In the case of residential biomass-fueled furnace systems, it can be assumed that the predominant proportion of particulate matter will occur in the particle size range of below 1 μm (Fig. 37) [2, 9, 25].

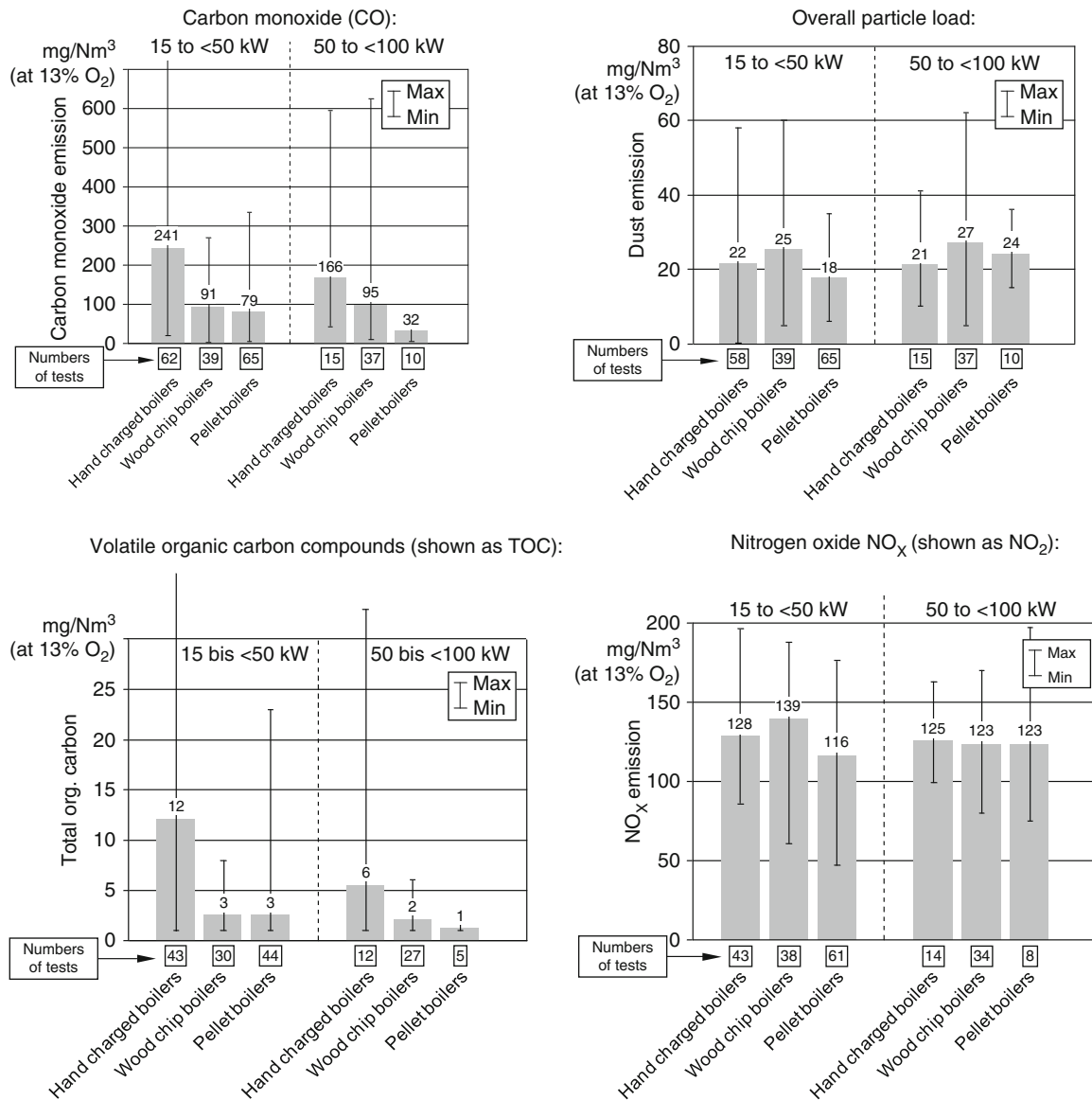
All measures aiming at a reduction in the overall emission of particulate matter will simultaneously also represent a measure for the reduction of fine particle emissions.

The possibilities for the achievement of additional reductions in the overall emission of particulate matter (and thereby of very fine particles), through specifically targeted further development of solid fuel combustion technologies (combustion geometries, air supply, other controls) have yet not been exhausted. Specially adapted control of air flows, for example, together with low levels of excess air (particularly within the vicinity of the fire bed) could help to achieve significantly more positive effects in the reduction of air pollutants emissions [30]. It should be possible to transfer the knowledge and experience gained in the introduction of such primary measures to small-scale furnace systems as well.

An additional factor is that, currently, science and industry both work on the development and testing of cost-efficient dust separation technologies as secondary measures. Conventional cyclones today, however, offer close to zero levels of efficiency in the separation of “submicron” particles (<1 μm), which do represent the major proportion of solid fuel emissions (Fig. 37). Current research therefore focuses primarily on the development of new filtering and electrostatic separation devices (e.g., metal netting filters, electrostatic precipitators, packed bed filters). Long-term operating experience with filtration systems for stoves or residential heating boilers, ready for series production, however, is rather scarce.

Even secondary heat exchangers, designed for the condensation of flue gases, do have a certain impact on the reduction of particulate matter emissions. These secondary heat exchangers are meanwhile commercially available on the open market for residential furnaces. In the case of wood chip combustion, the reported degrees of particulate matter separation are in the range of 20–40%, depending on the reverse flow temperatures of the heating system [13].

NO_x emissions. In most countries, there are generally no regulatory thresholds applicable to the emission of NO_x from wood furnaces in the small

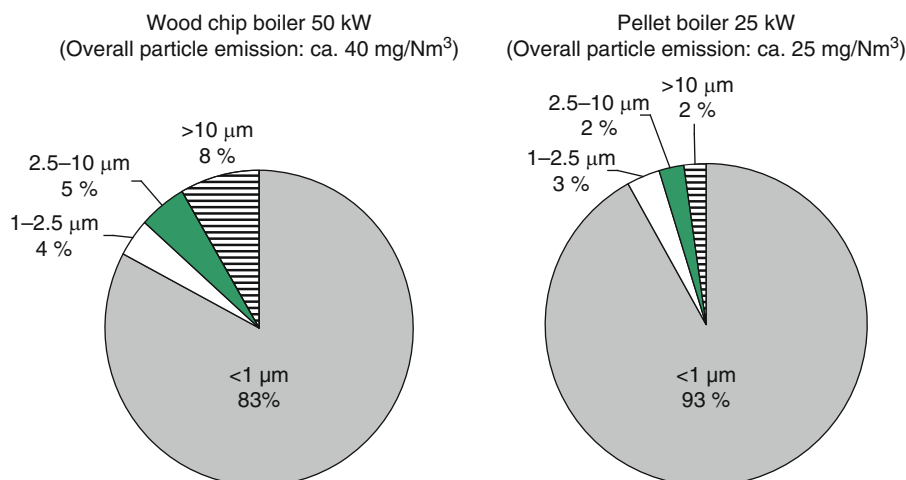


Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 36

Air pollutant emissions from wood-burning central heating systems – results from different boiler type tests for the 10-year period from 1996 to 2006 [12]

scale. Reference values specified by the German “Clean Air Act” (*TA Luft*) or by the thresholds of the German emission directive (*1.BImSchV*) could for example be complied with, without any problems, since untreated wood would generally be a comparatively low-nitrogen source of fuel. This applies in particular with regard to wood pellets, which are usually produced using sawmill

waste wood, and would therefore probably tend to show an even lower level of NO_x emissions, at nominal thermal energy output, than indicated in Fig. 36. This is particularly true since the systems would not be operated permanently at full output capacity. In contrast to the CO and TOC (total carbon) emissions scenarios, as outlined above, a reduction in the combustion



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 37

Representative results for the measurement of flue gas particle size distribution, resulting from the combustion of wood chip and wood pellets in residential central heating systems; measurements at nominal thermal energy output values [12]

temperatures, at reduced loads, actually does result in a reduction of NO_x emissions.

Secondary Flue Gas Treatment

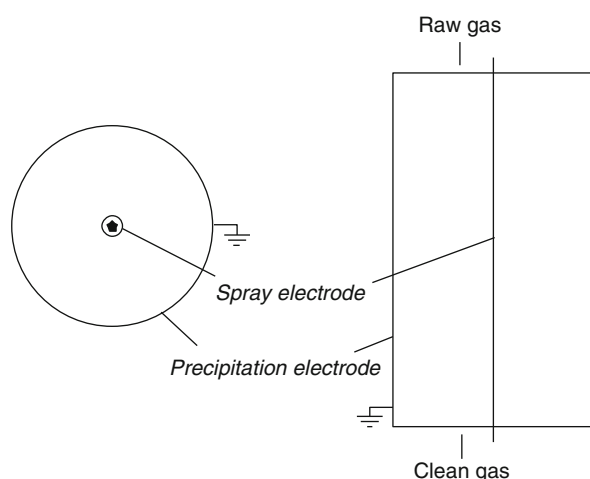
In the course of the debate concerning the reduction of particulate matter emissions from biomass furnaces, a need for action has been identified, in particular, with regard to stand-alone furnaces which so far do not have any dust removal systems installed in their flue gas systems. It can be expected that secondary separation systems will increasingly be used in future, especially in connection with the refitting of existing stand-alone furnaces (stoves). A number of different separation technologies can generally be employed in this context and their respective working principles and areas of application are described in the following sections.

Centrifugal collectors. Single-cyclone and multiple-cyclone separators, which remove dusts from the flue gas by way of centrifugal force, are standard fittings for wood chip furnaces in the medium capacity range. They demonstrate good performance ratings in the separation of particles with more than $1\text{ }\mu\text{m}$ diameter. Their performance, however, in the separation of the fine particle fractions does decrease drastically, so that

they are not suitable for small-scale heating systems whose emissions consist almost exclusively of fine particle dust.

Filtration collectors. The use of fabric filters (also known as bag house filters) in plants of less than 1 MW capacity is established practice. For small-scale systems starting at 30 kW capacity there are now some initial developments underway concerning the use of metal netting materials as well as cartridges for filtration purposes. A problem, at present, remains how to clean the filters without suffering a rapid increase in the loss of pressure, which would make a continuous operation without the support of additional blowers impossible.

Electrostatic precipitators. In the design of electrostatic precipitators (ESP) for stand-alone furnaces, a thin electrode (e.g., stainless steel wire) can, for example, be installed in the middle of a metal flue pipe (Fig. 38) and be connected to a high voltage supply (up to 30,000 V). The high voltage leads to the dust particles being charged and subsequently deposited on the inside of the metallic flue pipe, which acts as a collecting electrode. The layer of particulate matter created this way on the inside of the flue duct needs to be removed from time to time [31].



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 38

System diagram of an electrostatic precipitator (single-duct electrostatic filter) for stand-alone furnaces [27]

With the use of these types of separators (in field tests), the overall level of emission of particulate matter (including fine particles) could be reduced by 43–66%. In measurements taken under test bench conditions, levels in the reduction of emission of up to 80% have been achieved [9, 10, 20].

In other versions of this type of dust collector, several systems working in parallel are combined into a separate compact filtration unit, which can then also be cleaned periodically by means of a mechanical shaker system and a removable tray for ash residues. This type of dust collector is intended for use in small-scale wood boilers.

A common feature of all electrostatic separator systems is, that the area for the power supply of the spray electrode wire is ventilated by way of a small blower to prevent a short-circuit (i.e., disruptive discharge) caused in the duct through the potential settlement of particles. These types of multiple-duct electrostatic precipitator systems can achieve performance levels of up to 95% in separating efficiency [9, 17].

Electrostatic precipitators belong to the technically most advanced solutions currently available for small-scale furnace systems. Their theoretical operating performance, however, largely depends on three critical factors as demonstrated by Eq. 1:

$$\eta_G = 1 - \exp \left[-v_{eff} \frac{A_{NE}}{\dot{V}} \right] \quad (1)$$

where

\dot{V} is the volume of flue gas streams

A_{NE} is the separation surface of the collecting electrode.

v_{eff} is the flow speed which depends inter alia on particle size, particle load, temperature, pressure, and composition of the gas.

Tests with different combustion technologies using different materials of fuel from renewable energy sources have shown that electrostatic precipitators need to be adapted to the performance of the combustion system and to the fuel to be used, in order to be able to achieve constantly high and sustainable levels of separation efficiency.

An additional complicating factor is that the composition of the particulate matter in the course of the combustion process is constantly changing. During the initial combustion cycle, because of low temperatures, and usually too high a supply of oxygen, significant proportions of tar and condensable hydrocarbons are produced. In the course of the actual main combustion cycle, similar to the case of automatically charged furnaces, sulfides are formed, as well as increasing amounts of black carbon, because of insufficient supply of combustion air during the subsequent carbon combustion process.

The three categories of particulate matter can be differentiated by their respective properties of conductivity. The tar and condensable hydrocarbon substances show low conductivity and therefore produce an insulating layer on the electrodes following the separation process. The soot particles do possess such favorable conductive properties. They can be separated quite easily, and at the same time can be removed again from duct surfaces, where they have agglomerated in the form of coarser dust, so that reductions in the volume of mass are only limited. Only sulfides with a medium level of conductivity do demonstrate good separation and adhesion properties in relation to the collecting electrodes, allowing for efficient separation and discharge [29]. In order to prevent the otherwise particularly problematic buildup of tar and hydrocarbon deposits on electrode surfaces, many separation systems are bypassed during the initial stages of combustion.

Wet scrubbers and condensation systems. These can basically be divided into four different types of scrubbing technologies (Fig. 39).

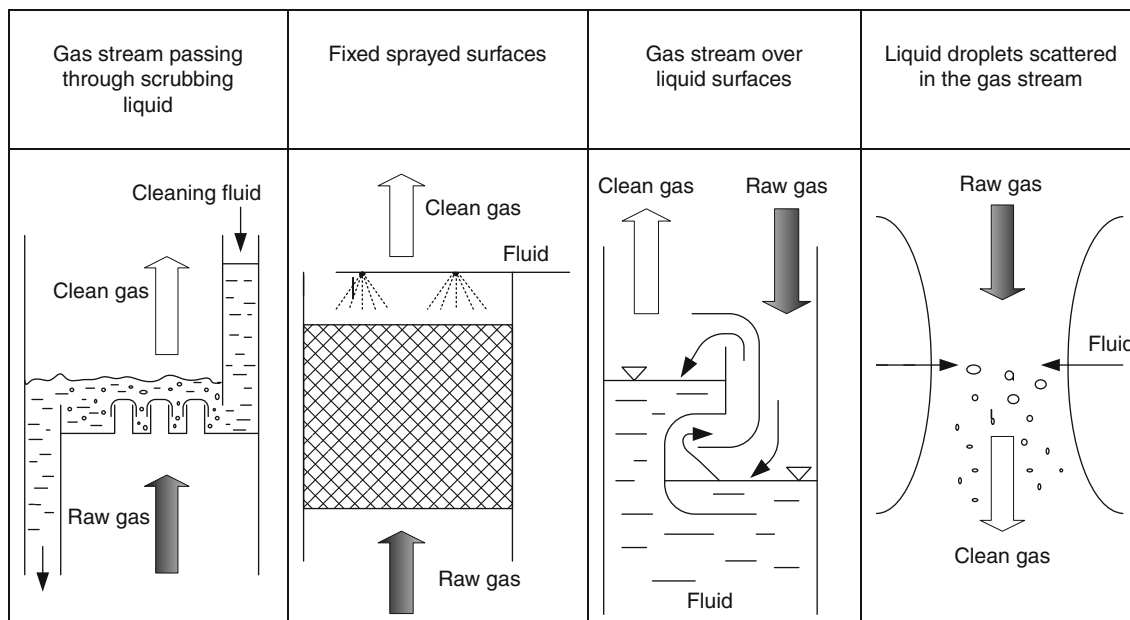
All four methods demonstrate certain deficits in terms of separation efficiency. In the case of gas streams passing through the scrubbing liquid, for example, separation efficiency depends largely on the size of gas bubbles (Fig. 39, left). In the case of net-coated surfaces being sprayed, the gas channel needs to be kept as flat as possible, in order to ensure a certain level of contact required in this process (Fig. 39, middle – left). The gas stream directed over liquid surfaces essentially follows the principle of inertia, although only with a limited degree of efficiency in the case of fine particles (Fig. 39, middle – right). The method of injection of droplets into the gas stream, in terms of separation efficiency, also largely depends on the size and density of the droplets (Fig. 39, right).

One feature common to all four scrubbing principles is the additional amount of effort and expenditure required for the handling of the scrubbing liquid. In the first place, it needs to be supplied and pumped to the location where the separation process is to

take place, and subsequently it has to be discharged, processed, and disposed after the separation process. Complete separation of dust-loaded droplets from the cleaned stream of gases is generally rather difficult to achieve.

Apart from the use of pure water, alternative scrubbing liquids and additives to scrubbing water are being tested. Special care needs to be taken so that substances likely to facilitate the absorbance of organic flue gas components are not liable to evaporate or ignite at the level of temperatures likely to occur in the separation process.

Whereas the development of a pure scrubbing system is currently still underway, a number of treatment systems have been developed and are close to being introduced to the market, whereby the partial separation of fine particles is achieved by way of flue gas condensation. The corresponding levels of separation efficiency presently still stand at around 20–40%. However, the primary benefits of this technology lie in the recovery of thermal energy from the water vapor contained in flue gas emissions (see section “Combustion Efficiency”).



Biomass Energy Heat Provision in Modern Small-Scale Systems. Figure 39

Separation principles used in wet scrubbers

At present, there is no uniform European regulatory framework governing the discharge of condensates produced by this process and regional regulations, in this respect, therefore need to be observed.

Through a combination of condensation and scrubbing technology levels in purification, efficiency in excess of 50% can potentially be achieved in future. With the benefits derived from the simultaneous recovery of thermal energy, these systems could also represent an economically feasible alternative to ensure that even very low thresholds for particulate matter, which may potentially be set for wood furnaces, could still be met in day-to-day operations.

Catalytic converters. In practical terms, however, the methods for secondary flue gas treatment described above generally have no impact on the reduction of gaseous emissions. Catalytic reduction could be an effective process to be employed in this context and a number of different systems for use of this technology are currently under development.

The difficulty for biomass-fueled combustion systems in this respect is that in addition to the gaseous substances resulting from incomplete combustion, significant particle emissions may be produced (condensed hydrocarbon compounds and black carbon), as well as dusts (not containing carbon compounds) resulting from ash forming substances contained in the biomass fuel. Whereas the gaseous components and to some extent also carbon-containing particles can be removed quite efficiently with the aid of catalytic converters, there is a risk that in the case of particulate matter not containing any carbon damage may be caused to the surfaces of the catalytic converter, or that caking may occur. Even with the installation of suitable cleaning systems, the risk of the catalytic layers wearing off cannot be excluded. It is therefore necessary to develop suitable catalysts and carrier materials, adaptable to the relevant ranges in temperature, while at the same time the long-term resilience of catalytic converters needs to be improved. The importance of catalytic separators also being used for the reduction of particulate matter emissions is further demonstrated by the results of current studies, according to which gaseous hydrocarbon emissions do significantly contribute to the overall level of fine particle emission through the creation of secondary aerosols [1].

Overall, it can be expected that in the coming years, integrated separators for small-scale furnace systems as well as separators suitable for the refitting of existing plants will be available on the market at reasonable prices. In the course of this process separator, technology and design will be adapted to the requirements of the relevant combustion systems and the respective types of fuel used, also in order to achieve a high degree of separation efficiency during continuous operations. For furnaces charged with biomass fuel it is likely, that the possibilities for both primary as well as secondary reduction in emissions will be exploited, in order to be able to meet the particularly stringent emission thresholds already imposed in a number of countries.

Future Direction

Based on the current state of technology, as outlined above, one can expect that the admissible levels of emissions – in particular with regard to fine particles – will continue to be lowered in future. Countries with existing emissions control regulations are in the process of severely tightening the relevant threshold values, or have recently done so already. In countries without corresponding regulations for small-scale furnaces, the imposition of threshold levels, or at least the introduction of benchmark values in the context of national standards, is currently under consideration. Europe-wide targets for particulate matter emissions could also be introduced under the recently revised Ecodesign Directive of the European Union.

Upper limits for particulate matter air pollution have already been defined under the EU Directive on Ambient Air Quality currently in force (Directive 2008 [50]EC). However, these limits are already being infringed, as a matter of course, in many densely populated, highly industrialized regions. Past attempts to regulate traffic pollution have rarely resulted in noticeable reductions. At the same time, studies investigating the sources of emissions have clearly identified the significance of wood-burning furnaces in this context. Based on this, it would seem to be merely a question of time until (at regional levels) the targeted reduction of particulate matter emissions from wood combustion will be enforced through regional anti-air pollution action plans. The reduction of dust and nitrogen

monoxide emissions from biomass-charged furnaces must therefore be further pursued, as a matter of urgency.

Complete combustion. The aim must be to achieve complete combustion for all furnace systems and operating conditions. For automatically charged furnaces this can be achieved, at reasonable costs, by means of suitable systems which, apart from oxygen levels in the air, also control temperatures in the combustion chamber and, if appropriate, the level of $\text{CO}/\text{C}_n\text{H}_m$ emissions. However, this is generally unlikely to be the case for hand-charged, stand-alone furnaces with predominantly discontinuous combustion characteristic. For these systems, the use of sensors, electronically controlled flaps, and motor-driven fans will become inevitable in future, even if today the traders still claim that, according to alleged customer demand, these types of furnaces are to be installed without electricity supply. In order to further reduce the impact of the recharging process, the downdraft combustion principle may establish itself as a promising alternative approach for these systems. In the case of chimney stoves, for example, the actual combustion chamber could be fitted with a glass screen to allow for the visual appreciation of flickering flames in the fire (chimney stove based on the design of a firewood-burning boiler with downdraft combustion).

Through the simultaneous achievement of significant improvements in combustion efficiency, the otherwise, in part, extremely high levels of emission of highly toxic polycyclic aromatic hydrocarbons (PAH), as well as large proportions of the constituent substances leading to the formation of secondary particles, would be substantially reduced. In this context, the use of catalytic converters could also serve to ensure low levels of emission in the event of short-term disruptions occurring in the combustion cycle.

Low emission furnaces. Assuming an otherwise largely complete stage of combustion, biomass-fueled furnaces will initially produce inevitable emissions of nitric oxide and fine particles, due to the nitrogen monoxide-forming and ash-forming substances contained in the fuel. Nevertheless, the goal must be to lower emissions to a level approaching that of oil and gas-fired systems. It is therefore also necessary to further improve the quality of fuels used in small-scale furnace systems. Current moves toward standardization provide product

norms to be introduced for wood pellets, miscanthus pellets, straw pellets, and reed canary grass pellets, as well as other types of fuel. Through the selective addition of appropriate aggregates, it should furthermore be possible, in future, to make appropriate adjustments for regional and seasonal variations in the relative proportions of trace elements.

In future, furnaces will generally have to show stable systems of separation between the pyrolytic decomposition and gasification zone as well as the zone of the full oxidation of the produced gaseous products. In order to be able to control output performance and/or cope with fluctuating combustion characteristics of the fuel used, methods need to be developed to adjust residence times and temperature levels, by means of the selective supply of air, even under rigid geometry conditions. The amount of primary air supply and fire bed temperature levels should be easily controllable and a suitable exhaust gas recirculation system may be required. The preheated secondary air supply has to be injected in such a way, that a thorough mixture and combination, even with hot combustion gases, can be achieved. Sensor technology and controls will be an essential prerequisite for optimal flow conditions and temperature profiles. For the reduction of NO_x emissions, a low-oxygen, high-temperature zone (approx. $1,000^\circ\text{C}$) could potentially be interposed between the primary zone and the combustion chamber.

The release of non-carbon-forming particles can be substantially reduced through measures such as optimal composition of fuels (agricultural biomass), low oxygen content, and low temperatures in the primary reaction zone. It should be possible to achieve future levels of particulate matter emissions below 5 mg/Nm and NO_x emissions of less than 100 mg/Nm , without any traceable amounts of hydrocarbon and with CO emissions near the detection limits. This can be supported through the use of integrated dust collection zones and, if appropriate, integrated or downstream fine particle separator systems.

In conjunction with an improvement in combustion performance and flue gas condensation, there will also be an improvement in the level of efficiency of the combustion system. Flue system fans, also if used for stand-alone furnaces, do allow for a noticeable reduction in flue gas temperatures and therefore a significant reduction in flue gas losses. Chimney systems,

therefore, in the future, should be moisture resistant, since the risks of potential occurrence of condensation in the flue system can no longer be safely excluded.

Optimization of systems. Beside improvements to be made to the actual furnaces, optimization of the overall systems is likely to gain importance. In order to be able to achieve low levels of emission and a high level of annual efficiency, boiler systems will need to be adapted specifically to the relevant buildings, existing heaters (e.g., solar thermal installations), and the particular user behavior. Apart from the control systems, which need to be taken into consideration in this context, the user also has to be involved interactively, in the sense of managing supply and demand, by way of consumption meters as well as displays indicating the available supply of renewable thermal energy stored in the buffer system (smart metering).

Alternative concepts need to be explored in order to reduce the heat storage losses during boiler shutdown periods. Thermal insulation to some extent might also be further improved in this context. Possible savings resulting from these measures, however, could potentially still be exceeded through the use of latent heat storage units and/or minimization of storage volumes. Allowing for a continuing decrease in space-specific heating requirements, it seems to be possible that through the use of sensitive demand forecasting tools, industrial water storage, and large-scale storage capacities in buildings (activated floors/ceilings), significantly smaller and more compact biomass-fueled furnaces could be installed. Smaller designs would allow for faster passing through the start-up and shutdown phases, which produce high levels of emission, and at the same time noticeably reduce losses from the cooling down process. This would significantly contribute toward a reduction in emissions, if an increase in the number of starting phases could be prevented by way of an intelligent control.

Operational safety. Excessive levels of emissions from stand-alone furnaces and potential disruptions of the combustion cycle, as well as hazards caused by users otherwise, can be minimized through the increased use of flue gas sensors and other system control mechanisms. The installation of CO and/or C_nH_m sensors in small-scale furnace systems, in combination with the appropriate electronic controls, will always prompt the release of a warning signal. This is

true if, for example, the level of humidity of the fuel being charged is likely to cause a disruption to the combustion cycle, with the resulting emission of hazardous concentrations in terms of air pollutants. In such cases, for example, the installation of suction fans could ensure that no potentially hazardous or air-pollutant substances do enter into the living space, particularly when the door to the stove is opened for recharging.

Conclusions

Modern small-scale systems for the supply of heat using solid biomass fuels, and wood in particular, have already reached high standards of quality in terms of combustion efficiency. Further improvements, however, in combustion and furnace technology, including secondary measures for the reduction of emissions, are essential in order to be able to also meet increasing future demands in respect of the reduction of particulate matter and NO_x emissions, as well as allowing for the increased use of biomass fuels, without corresponding increases in the emission of polluting substances. This is technically feasible. Thus the objective must be in the medium to long term not to exceed the levels reached with present day oil- and gas-based combustion technologies. Stand-alone combustion plants, at least, should in the long term not be allowed to operate without an efficient active air control systems. Present priorities concern improvements in the integration of stoves and boilers into the overall heat supply systems of buildings. In the medium term, the simultaneous and combined supply of heat and power, as well as the potential supply of cooling systems during summer temperature conditions, is likely to gain increasingly in importance.

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Biomass Energy Small-Scale Combined Heat and Power Systems

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Article Outline

Glossary
Definition of the Subject
The Global Importance of Micro Cogeneration
Conversion Technologies for Small-Scale Heat and Power Systems
Market Survey
Conclusions
Future Directions
Bibliography

Glossary

Cogeneration Cogeneration (combined heat and power – CHP) describes the use of one source of energy in a plant for the simultaneous supply of heat and electric power.

Plant operating mode The operating mode of CHP plant can be divided into two categories. *Heat-controlled operation* means an operation of the plant according to the thermal energy demand of the heat consumer. In contrast, *power-controlled operation* is determined by the demand for electricity or a maximum power generation. The heat that cannot be used is stored for later usage or is disposed by a cooler.

Small-scale cogeneration unit So far, there is no generally applicable definition of the power range of small-scale CHP plants. In the context of this entry, small-scale or micro CHP plants are Cogeneration units with a maximum electric output capacity of 50 kW.

Status of development Four categories of development stages for cogeneration applications can be defined. *Research and Development* describes the stage of new technologies under laboratory conditions. Plants in *Demonstration* exist as prototypes of their later commercial versions and are subject to field-testing with regard to their suitability for everyday use. Further optimization is under investigation. In case of positive field-testing follows the phase of *Commercialization*. The first produced plants (often also referred to as pilot series) are introduced to the market. Once a plant or technology has been established on the market and has been accepted by the users one refers to *Market Diffusion*.

Definition of the Subject

Combined heat and power (CHP) generation is one of the essential pillar in a modern, sustainable, and environmentally friendly energy generation. This is due to the fact that cogeneration systems are energetically efficient and produce energy where it is needed. There major advantages include a substantially increased fuel efficiency, reduced emissions of CO₂, reduced need for transmission and distribution networks, and a beneficial use of local energy resources (e.g., through the use of waste and biomass).

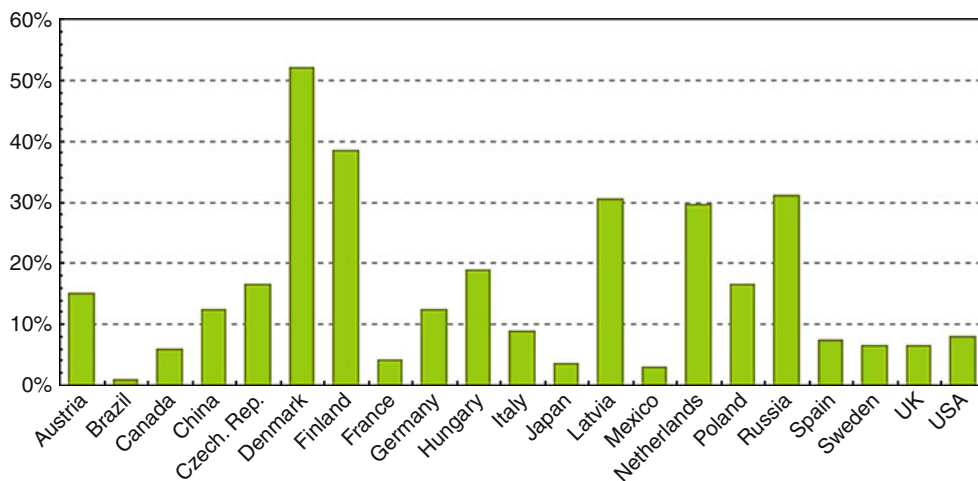
At present, only approximately 10% of the global electricity generation is done by CHP. Exceptions are some European countries, like Denmark and Finland, which have successfully expanded the use of CHP up to

30–50% of total power generation during the last years (see Fig. 1) [1].

Given that the majority of the CHP plants mostly are driven by fossil fuels (see Fig. 2), it is obvious that the global relevance for biomass-driven combined heat and power generation is still at an extremely low level. In 2007, approximately 5.5% of total energy consumption by end users in the EU, Turkey, and Norway was covered by wood and wood chips, approximately 8% of heating requirements in private households was covered by solid biomass and very few of both in

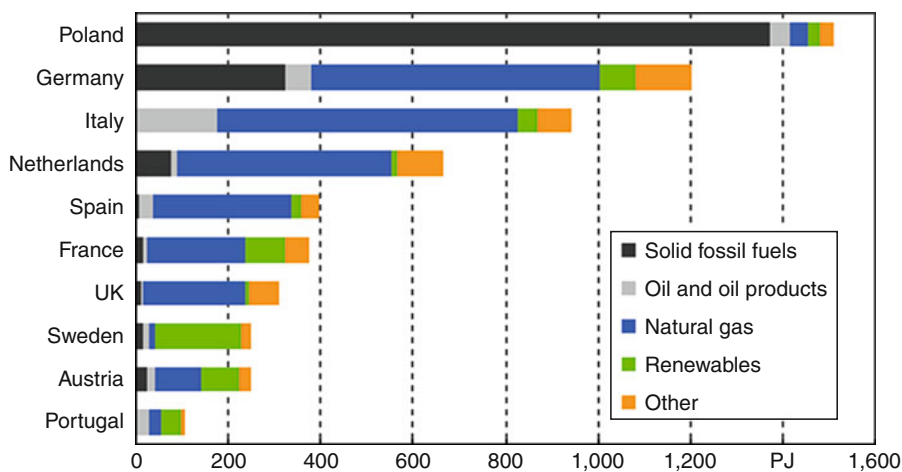
CHP [2, 3]. With a growing world population and increasing economic development in the emerging markets biomass, on the background of climate protection targets, will continue to gain importance worldwide. Due to limited resources, a more efficient use of the potentials available will become of increasing significance in this context.

The supply of heating to private households and the commercial sector by using biomass has gained increasing importance for a number of years. In this field, the demand for and interest in CHP units has also



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 1

CHP share of the national power production [1]



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 2

Fuel input in CHP by country (selection) [4]

grown significantly, whereby the majority of the already installed micro CHP units are still operating with fossil fuels. For using biomass within small-scale CHP systems, it is therefore of fundamental importance that appropriate cogeneration plants become available on the market.

This entry therefore provides an overview of the global importance of biomass micro cogeneration and the established technological approaches in cogeneration on the basis of solid, liquid, or gaseous biofuels in the range below an electric capacity of 50 kW, subsequently describes selected concepts in their current stage of development (laboratory, demonstration, market introduction, and market ability) and delineates the suitability of biomass-driven micro cogeneration for different areas of application. The presented options are compared and perspectives for future developments are highlighted, also taking into consideration new approaches in technology.

The Global Importance of Micro Cogeneration

Below some examples for the global importance of cogeneration in general are given.

Europe

The landscape of power plants in Europe is currently undergoing a process of change. Reasons for this can be found in the general political environment (e.g., regulation of the energy markets, national and international climate protection targets), in the expected development of the use of renewable energies, and in the expected massive shutdown of fossil fuel power plants exceeding their technical life time in the years to come. The resulting demand for power replacement of up to 14,000 MW in respect of the power plants scheduled to go off the grid for example in Germany by 2020 [5] does represent a major opportunity for the introduction of new technologies.

There are a number of facts determining the development of power demand from private households, small enterprises, and public sector institutions during the next decade. Whereas the utilities expect a continuous growth in the consumption of electricity, due to climate protection reasons the Ministries and the politics assume a decrease in electricity consumption, whereby the greatest potential for this is seen in the

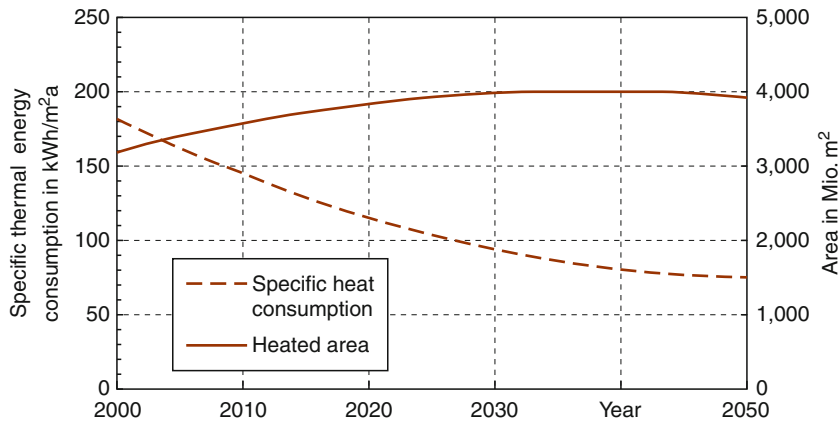
industrial sector. There are no noticeable savings expected for private households. If the experiences from the past are transformed to the future, a further increasing electricity demand is more likely than a decreasing demand.

In addition to that, energy-saving measures are more and more implemented within the heating sector through a much better insulation. As a consequence it can be expected that the specific heat demand will continue to decrease in future. For example, the Lead Scenario 2009 commissioned by the German Ministry for the Environment predicts a reduction in average heating requirements within the residential housing sector in Germany by 2020 of approximately 80% referring to the present level taking into account that the average specific living space will grow by around 10% within the same time period (Fig. 3).

Northern America

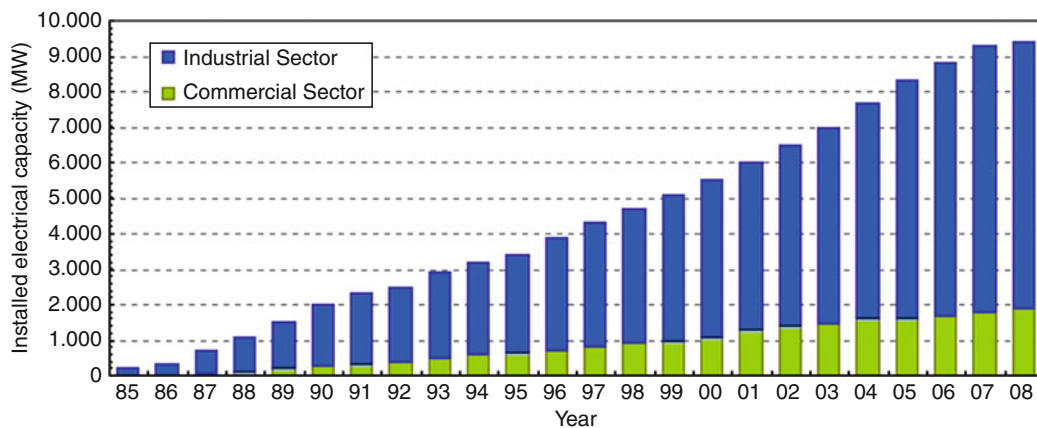
The establishment of (micro) cogeneration systems on the northern American market is more difficult than it is on the European market. In 2001, the US Environmental Protection Agency (EPA) has established the combined heat and power partnership. The CHP partnership promotes CHP by creating and fostering cooperative relationships with the CHP industry, state and local governments, and other relevant stakeholders. From 2001 to 2009, the program had supported more than 460 projects, representing a total electrical capacity of 4,850 MW [7].

A significant increase of the micro cogeneration is hampered, among others, by the following reasons [8]. In northern America, the distribution of the heat is often done by systems using air, rather than water. The exhaust heat of micro cogeneration systems commonly is recovered in water-filled cooling cycles. Therefore, an additional step is needed to transfer the heat from the hot-water to the air distribution systems. Furthermore, the cost of hot-air heating systems (e.g., stoves) is commonly much lower than the cost of water-filled heating systems (e.g., boiler). This means that the difference between a micro combined heat and power generation system and a heat generation system is much higher than, for example, in Europe. Another important point is the low energy price in many northern American regions, which makes it harder for micro



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 3

Development of the heated area and the specific thermal energy consumption for existing residential buildings exemplarily for Germany [6]



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 4

Accumulation of installed cogeneration electrical capacity in MWel in Japan, from 1985 to 2008 [9]

cogeneration systems to operate with a clear economic advantage. Despite these reasons, there is a great demand for micro CHP systems being able to work in isolated operation mode.

Japan

The Japanese government has supported ambitious energy targets to reduce the dependency on imports of fossil fuels and to address climate change. As a result, the installed cogeneration capacity has increased substantially over the last 20 years. In 2009, over

9,200 MW_{el} of installed CHP (see Fig. 4) provided around 4% of the country's electricity generation. The major cogeneration technologies used in Japan are gas turbines, diesel engines, and gas engines.

Industrial cogeneration installation represents approximately 80% of the installed electrical capacity. The remaining 20% are commercial and domestic CHP applications. Typical installations are in hospitals, hotels, office buildings, and sport facilities. The electrical capacity of available micro cogeneration systems is typically smaller than 10 kW. One important unit is the gas-engine micro CHP unit Ecowill, with an electrical

capacity of 1 kW and a thermal capacity of around 2.8 kW. In 2010, the worldwide and cumulative sales of the Ecowill have passed the 100,000 mark. The majority of the units were sold in Japan. This has meant that Japan is the world leader in the development and implementation of micro cogeneration technologies at the domestic household level. Japan is also a step ahead of developing Fuel Cells, seeing the market launch of Fuel Cells in 2011–2012.

Conversion Technologies for Small-Scale Heat and Power Systems

In the following, the main technologies for small-scale cogeneration on the basis of solid, liquid, or gaseous biofuels are presented.

The listing starts with piston-cylinder devices (e.g., internal combustion engines, steam piston engines, and stirling engines) as they are the best developed systems for small-scale cogeneration in general, followed by technologies generating electricity using turbines (e.g., steam turbine, hot-air turbines, and micro gas turbines) and concludes with fuel cells and thermoelectric generators.

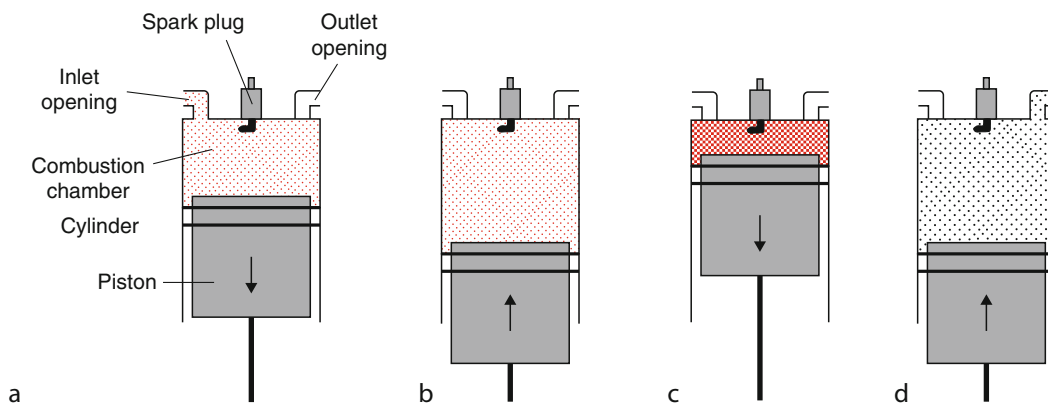
Internal Combustion Engine

Due to the longstanding experience with engines operating with Diesel, gasoline, or Methane, as well as fossil fuel powered CHP plants, internal combustion engines represent the most proven technology for the

cogeneration of heat and power. In a combustion engine the fuel is compressed and then ignited. The subsequent expansion sets the power piston in motion and brings the engine shaft into rotation. A generator converts the mechanical energy of the engine shaft into electric energy (see Fig. 5).

Engine-driven CHP plants with electrical capacities ranging from a few kW up to several MW are available and established on the market. The levels of electrical efficiency thereby range from 25% to 40% and the own internal electricity consumption requirements range between 5% and 10% of the output. From an engine perspective, the quality of the liquid or gaseous fuel is the essential criteria for selection. Due to the high level of noise emission, appropriate sound-insulation measures are necessary. The maintenance requirement for combustion engines lies significantly below that for comparable (micro) gas turbines. The investment costs per installed electrical capacity for combustion engines in the low-capacity segment range from 1,000 to 2,000 €/kW.

Due to the internal combustion, only liquid or gaseous biofuels can be used directly. The use of solid biofuels requires a pre-step gasification. Currently, the majority of biomass micro cogeneration plants available on the market are internal combustion engines operating with biogas (Fig. 6). The major advantages of internal combustion engines are the long history, large production and service infrastructure, and the generally lower power generation costs. Nevertheless,



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 5

Operation principle of an internal combustion engine (a) Air-fuel mixture is drawn in; (b) Air-fuel mixture is compressed; (c) Explosion forces piston down; (d) Piston pushes out exhaust



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 6
PowerTherm® micro-CHP unit (Copyright by PowerTherm Energie Systeme GmbH)

despite these advances most biogas combustion engines are sited on farms and landfill sites with a direct source of biogas feed stocks. For the energy supply of private households and small business and community facilities it currently only plays a subordinate role [10].

Because of technical problems, a heavily fluctuating price of vegetable oil during the last years and the increased public discussion about the direct competition with the food production the use of vegetable oil stagnated on a lower level. Irrespective of these problems there are a few companies (mostly from Germany) that offer solution compatible with vegetable oil.

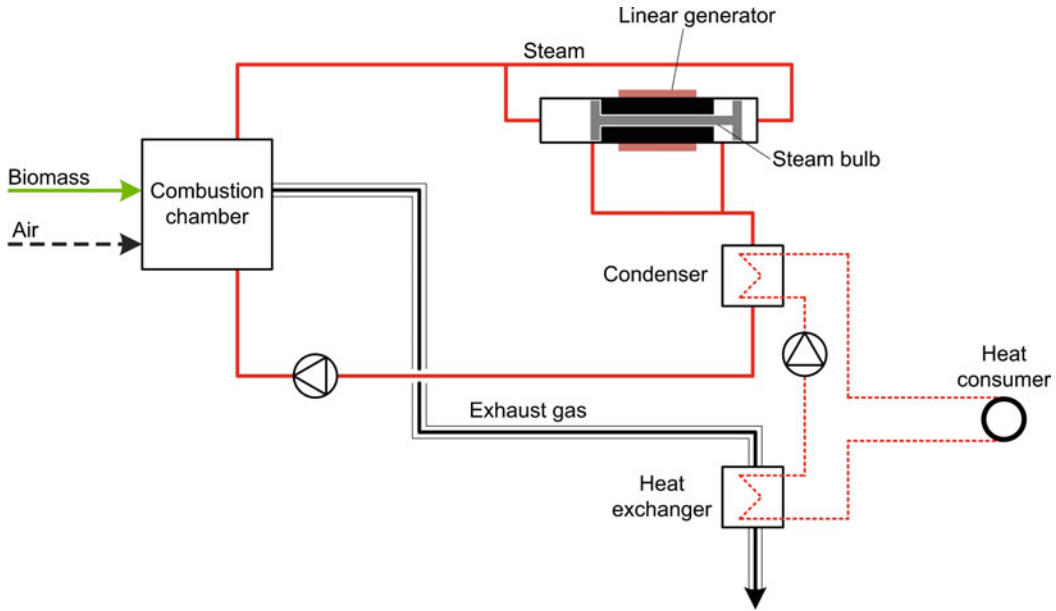
Steam Piston Engine

Steam piston engines are steam pressure engines where the expansion of steam takes place in a piston engine. Steam piston engines can comprise up to six working cylinders, whereby each cylinder has a piston rod, which controls the required amount of steam through

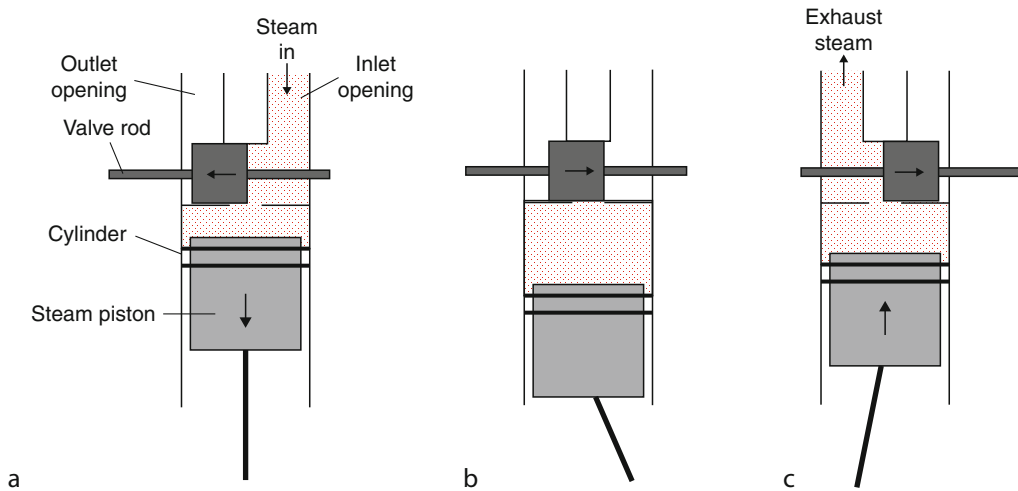
the corresponding stroke. Apart from a two-shaft version also a free-piston steam engine has been developed, comprising two steam cylinders connected by a double free-piston. Since the use of conventional generators for this version is not possible due to the missing shaft rotation, a linear generator has been integrated into the engine (Fig. 7).

At the beginning of the process cycle, steam flows into the cylinder until the valve rod terminates the intake process (Fig. 8). The steam subsequently expands in the working chamber and drives the steam piston. The volume increases and the pressure reduces. Having reached dead-center position, the valve rod releases the outlet valve and the steam is discharged from the cylinder. The energy transferred to the piston is passed on to the output shaft via a connecting rod and converted into electric energy in the generator connected to the system [12].

Steam piston engines, in contrast to steam turbines, can be operated with saturated steam as well as with dry steam. Due to the significantly higher level of usable



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 7
System diagram for a biomass CHP unit with free-piston engine and linear generator [11]



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 8
Operation principle of a steam piston engine **(a)** Steam intake; **(b)** Pressure reduction and mechanical work; **(c)** Steam outtake [12]

thermodynamic heat content (enthalpy) available through the use of dry steam substantially, higher rates of electrical efficiency can be achieved.

Steam piston engines demonstrate very good rates of electrical partial load performance and in

comparison to steam turbines they are less susceptible to any potential contamination of steam. However, the electrical efficiency with 6–15% is rather low. Additionally, steam piston engines show a high level of maintenance for plants requiring lubrication; this is not

necessarily true for plants not requiring lubrication. But such engines show noise emissions of up to 95 dB(A).

Due to the closed steam power cycle in steam piston engines, there are no restrictions on biomass-based fuels, which may be used for steam generation. Steam piston engines can be employed in the range from a couple of 10 kW up to several MW.

Steam Screw-Type Engine

The working principle of the screw-type engine corresponds to the classical steam turbine process with the difference that the expansion of the steam does not take place in a turbine but in a screw-type engine.

Screw-type engines consist of two screw-shaped interlocking rotors that are closely encased by the engine housing (Fig. 9). The working chamber is created by the space between the rotors and changes cyclically during operation. At the beginning of the process cycle, the working medium flows through the intake opening into the space between the rotors. The rotation of the rotors closes off the inlet cross section thereby creating a sealed off working chamber. During the

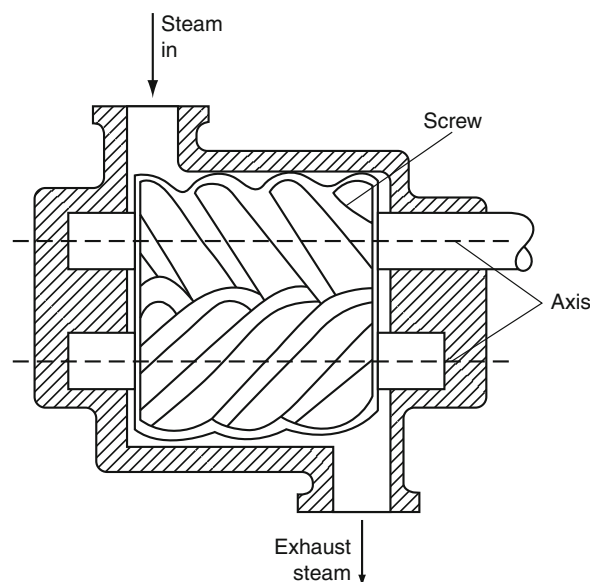
expansion process, the steam flows through the space between the rotors, which widens toward the outlet opening. The steam expands in the process and converts its thermal energy into a rotational movement of the rotors. The mechanical energy generated this way can be converted into electric energy through a directly connected generator [13].

Two types of steam screw-type engines are distinguished: wet and dry operating engines. For wet operating engines, oil is injected into the working chamber for lubrication of the engine and sealing of the rotors. Following discharge from the engine, this oil needs to be separated again from the condensate through appropriate oil extractors. Dry operating engines achieve contact-free movement by means of a special synchro-mesh transmission. The separately required lubrication of the rotor bearings can be performed through closed labyrinth seals. The advantage of this construction design is that the oil separator does become obsolete. The necessary gap between the two rotors however leads to higher losses of energy compared to wet operating screw-type engines.

For the generation of steam – as is common for systems with external combustion – different sources of heat and fuel can be used. The requirements on fuels thereby increase with declining plant capacities, since smaller plants usually also feature smaller heat exchange surfaces and profiles. As is the case for steam turbines, apart from water also organic fluids may be used as working medium. Steam screw-type engines demonstrate a high level of tolerance with regard to the quality of steam and can be operated with saturated steam as well as with dry and wet steam. In contrast to steam turbines there is no danger of droplet erosion in this case, so that expansion up into the region of wet steam is possible.

Further advantages of steam screw-type engines compared to other heat generating plants are their favorable partial load performance and low maintenance and operational requirements. A disadvantage is the high noise level, which allows for residential housing applications only with the implementation of appropriate sound-insulation measures.

Screw-type engines are generally suitable for the decentralized generation of electricity and heat supplies in the electrical capacity range between 20 and 2,000 kW, whereby no their suitability in the lower



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 9

Operation principle of a steam screw-type engine [12]

capacity range has not been proven yet. The rates of electrical efficiency are in the range of 10–15% [13, 14].

Stirling Engine

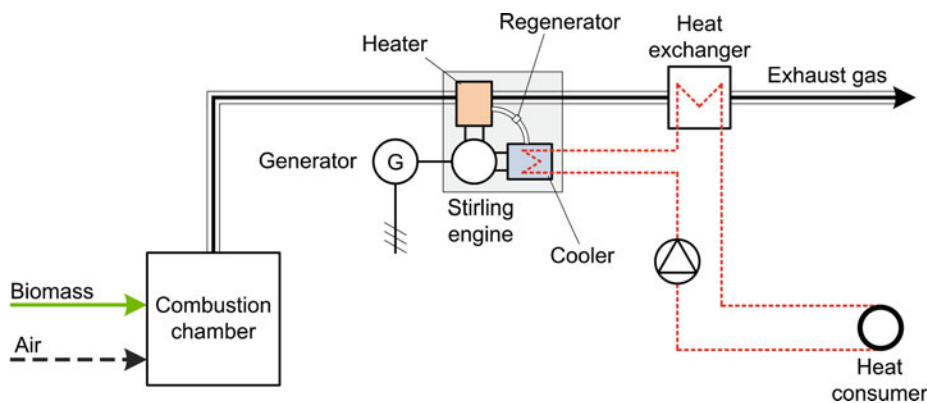
The Stirling engine belongs to the hot gas and expansion-driven engines where the piston connected to the generator is not driven directly by the expansion of combustion gases. The power piston and working gas form a closed system whereby the expansion of the working gas is caused through the supply of energy from an external heat source. In this way, Stirling engines can generally be used and optimized independent of the type of heat generation process.

Stirling engines are available in a variety of designs, which essentially only differ in the arrangement of the expansion and compression cylinders. Characteristic for all designs is the use of a constant amount of working gas (air, helium, hydrogen, nitrogen) in a closed cycle. Every Stirling engine has a high-temperature section and a low-temperature section (in Fig. 10 referred as heater and cooler) between which the working gas is cyclically moved back and forth between the expansion and the compression cylinders (Fig. 11). Depending on the design, the pistons will move at an angle of between 60° and 90° to one another in alternating phases. In single-cylinder systems, by contrast, both pistons are housed in one chamber. The conceptualized process consists of the compression and the expansion phase. During the expansion phase, the working gas expands under

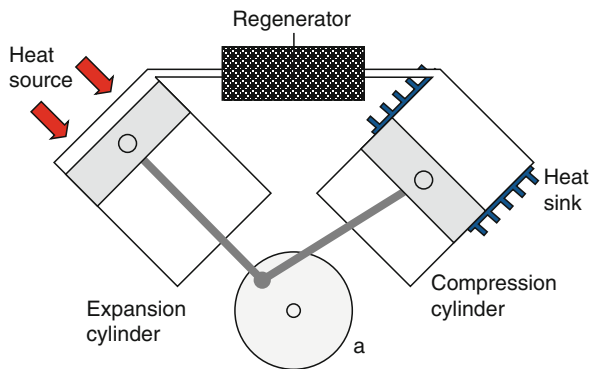
the external supply of heat leading to an expansion of the gas. The hot working gas flows through the regenerator toward the compression cylinder and release its thermal energy to the heat sink. In the compression phase, the working gas is once more compressed through the power piston and pushed back through the regenerator into the high-temperature section [15].

The advantage of the Stirling engine lies primarily in the use of an external source of heat. This way, the external combustion can be optimized independent of the operational status of the Stirling engine. Due to its closed cycle design, the average useful lifespan of a Stirling engine will generally also be higher than that of a comparable power generating system. To be set against this are the high demands placed on the seals, which occur with the use of helium as working gas. Regular checking and if appropriate also refilling of the working gas may be necessary, in part. For some models, this leads to a significant increase in operating costs. Additional problems might cause deposits at the heater/heat exchanger. In the case of long servicing intervals, the use of high-quality wood pellets is required for optimized combustion with low particle content within the hot flue gas. In the case that firewood or wood chips are used more frequent servicing intervals are advisable.

Since the combustion does not take place in the Stirling engine itself, and since there are no valves, only limited noise emission and vibrations occur during operation. Driven by the growing interest in technical solutions for small-scale power generation the



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 10
System diagram for a biomass CHP unit with a Stirling engine [12]



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 11

Operation principle of an alpha stirling engine with two cylinders

development of market-ready stirling engines has accelerated significantly in recent years. In this context, the latest developments have shown that biomass in form of wood pellets or firewood is well suitable for use. There are currently a number of stirling engines with electrical capacities between 1 and 100 kW in the demonstration and market introduction phase. Provided that a heat sink on a low temperature level and high flue gas temperatures at the heater are available, electrical efficiencies of around 25% can be achieved. However, due to lower flue gas temperatures emitted during biomass combustion the electrical efficiency of biomass-fueled stirling engines tends to be significantly lower. This option is still within the R&D-status.

Steam Turbine

The generation of electric power through steam turbines takes place in a thermodynamic process cycle. Here either water or an organic working medium is circulated within a closed cycle. Common features of all steam turbines are blades on the turbine shaft and casing.

Steam turbines are available in a large variety of construction designs. They can generally be distinguished by their direction of flow. In axial turbines the steam passes through the turbine in parallel to the axis, in radial turbines at a right angle to the axis. Applications for use of both designs can be found in the low electrical capacity range (<100 kW).

In the steam process the working medium is evaporated and subsequently superheated. The superheated

steam is channeled between the blades setting the turbine shaft into rotation. The generator connected to the turbine shaft converts the mechanical energy into electrical energy. The steam emitted from the turbine is channeled to a condenser where it discharges most of its still remaining thermal energy into a heating cycle, whereby the steam condenses. The condensate is channeled back into the system.

Water is used as working fluid in the classical steam process. High pressures and high temperatures are required to maximize the energy content of the steam and thus the overall efficiency. In the Organic Rankine Cycle (ORC) process, an organic working medium (usually silicon oil) is used instead of water and an additional thermal oil cycle is often introduced, resulting in increased space requirements and higher costs of investment. In contrast to water, the organic medium has usually significantly lower steam pressure. Therefore, there is no need for the installation of expensive high pressure systems. The thermal oil is heated up to a supply flow temperature of approximately 300°C and then channeled onward into an evaporator where the organic working medium is evaporated through use of the heat transferred by the thermal oil into the ORC process. The steam is expanded in a slow running turbine where it performs mechanical work, which produces electric power within the generator. The expanded steam can afterward be used in a regenerator for the internal recovery of heat. In the downstream-installed condenser the working medium in condensed releasing still remaining heat to external consumers. Following this, the working medium is brought back to operating pressure and again channeled into the evaporator.

Steam turbines in the MW capacity range represent proven technology for the generation of electric power with high levels of electrical efficiency performance of up to 45% (Fig. 13 shows the rotor of a 250 MW industrial steam turbine) [16]. A drawback in the development and market introduction of small-scale steam plants are the much lower electrical efficiencies with a concurrent significant increase in specific costs. In the segment of micro cogeneration units, additional technical problems arise due to the need for miniaturization of turbines, which can be resolved only through increased expenditure in construction. All in all, this has led to a situation where there are no market-ready

micro steam turbines available in this segment. The capacity range available on the market starts in the range of several MW.

ORC plants for the conversion of waste heat from biomass-fuelled plants in the electrical capacity range of 400 kW to 2.2 MW are today state of the art. But the 10–15% level of electrical efficiency that can be achieved remain significantly below those for steam turbines [17]. Work is currently being done to reduce in power capacities, whereby development activities until now have generally been limited to an assessment of basic technical viability without taking into consideration short-term commercial interests. The partial load performance of ORC plants is comparatively good. The advantage compared to steam turbines lies furthermore in the automated operation without the need for permanent control of the status of the steam cycle and in the possibility of decoupling heat at different temperature levels (condenser and economizer in Fig. 12).

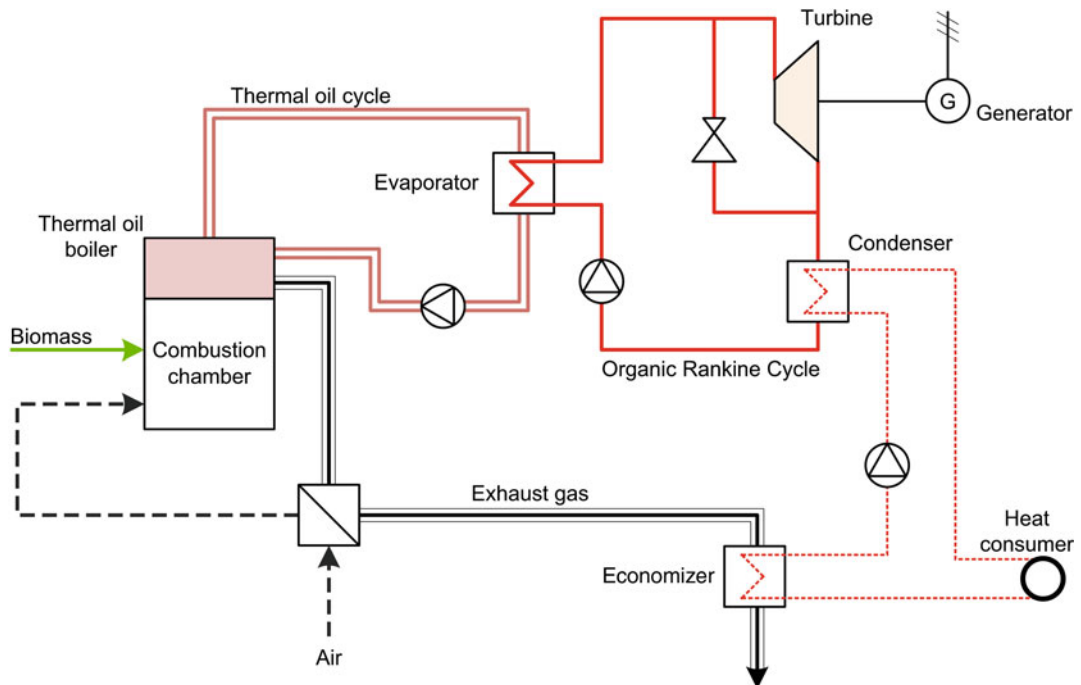
Since steam turbines are closed systems with external heat generation, essentially all available biomass

fuels for the generation of steam can be used. Similar to stirling engines, the heat transfer surfaces may need to be formed in such a way that the risk of deposits is minimized. The emission of noise from steam turbines is typically rather significant due to the high rotational speed of the turbine shaft. This makes appropriate sound insulation and vibration control necessary. Due to their slower rotational speeds, ORC plants can be expected to demonstrate lower levels of noise emission.

The investment cost per installed electrical capacity of an ORC module range from 2,000 to 3,000 €/kW. For an ORC plant (including thermal oil boiler, electrostatic precipitator, and thermal oil) the specific costs will increase by around 1,000 €/kW.

Hot-Air Turbine

Within a hot-air turbine, hot air expands inside the gas turbine. The hot flue gas transfers its heat in a high-temperature heat exchanger to the working air, which has already been compressed within the compressor. This compressed working air is heated up to



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 12
System diagram for a biomass CHP unit based on an Organic Rankine Cycle [12]

approximately 800°C. Then it expands in the turbine to ambient pressure and a temperature of approximately 400°C while performing mechanical work. Subsequently the expanded working air is channeled through a heat exchanger, warming up the combustion air



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 13

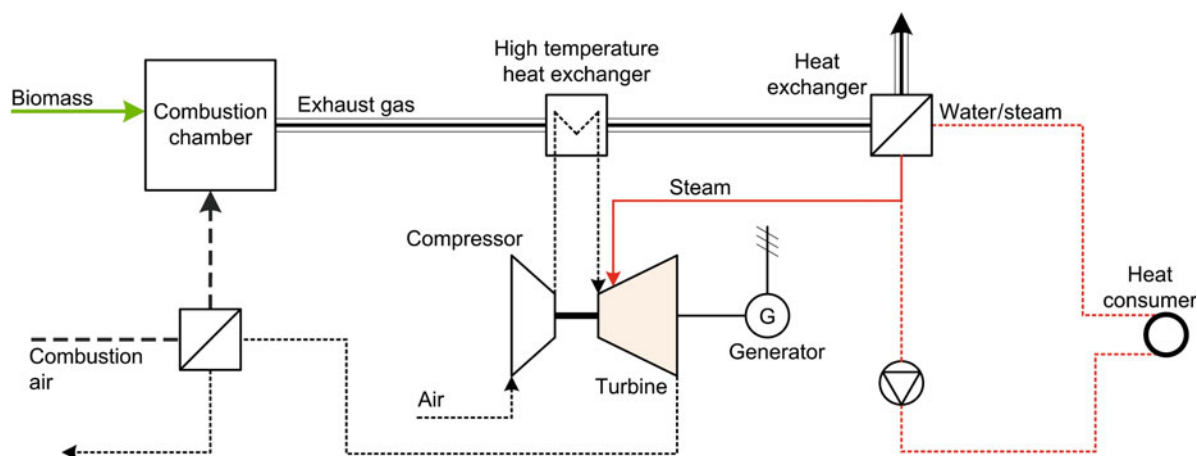
Steam turbine (Copyright Siemens AG)

needed to provide the thermal energy. The heat remaining in the flue gas at approximately 300°C, can be used for the generation of steam or hot water (Fig. 14). This comparatively high temperature level also allows the generation of electric power by a downstream ORC installation.

Due to the closed air circuit, any type of fuel can generally be combusted in the boiler. The degree of electrical efficiency of hot-air turbines ranges from 10% to 20% [18]. The smallest turbine available, at present, has an electrical output rating of 25 kW with a price of up to 8,800 € per installed electrical capacity in kW. Technically challenging are the high-temperature heat exchangers, which are rather expensive given the high demands placed on the materials used, as well as the limited long-term operating experience available to date. Therefore, this option is basically within the R&D-status.

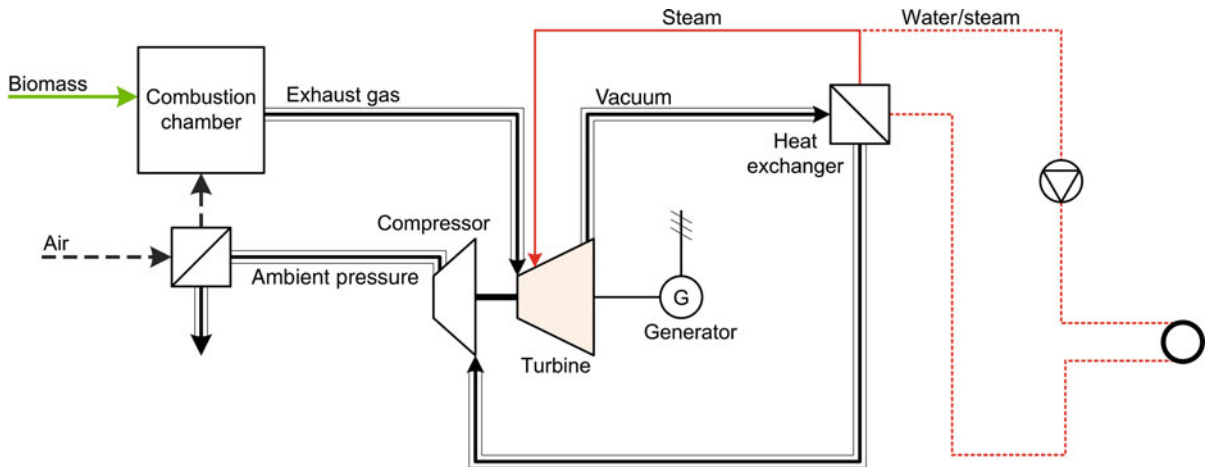
Inverse Gas Turbine

In contrast to the classical gas turbine process within the inverse gas, turbine process combustion takes place at atmospheric pressure. The flue gas released from combustion at a temperature of around 1,000°C is cleaned in a high-temperature cyclone or hot gas filter and then cooled down to around 700°C through the injection of water or steam. Then the flue gas passes into the gas turbine where it expands from the ambient pressure range into vacuum pressure of approximately



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 14

System diagram for a biomass CHP unit with hot-air engine and steam injection [13]



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 15
System diagram for a biomass CHP unit with inverse gas turbine and steam injection [13]

0.3–0.4 bar and performs mechanical work. The heat of the expanded flue gas can subsequently be used in several steps for the generation of high and low temperature heat. The cooled down exhaust gas, still in the vacuum pressure range, is compressed within a compressor to reach ambient pressure and heated up in the process (Fig. 15). The heat generated this way can, for example, be used for the preheating of the combustion air. The exhaust gas is subsequently released into the atmosphere – if necessary, having first gone through an appropriate cleanup process [19, 20].

Inverse gas turbines can generally be used in an electrical capacity range from only a few kW up to several MW, at rates of electrical efficiency of around 20%. The operating experience necessary for an assessment of maintenance and operational requirements is, at present, not yet available. With the use of standard components for the turbine and peripheral components, it can be assumed that no significant problems should arise. Due to the early stage of the development, no statement about the future price is possible.

An important argument for the development of inverse gas turbines – apart from the advantage derived from atmospheric combustion, which through the use of biomass avoids the otherwise costly fuelling through a pressure vessel – is the possibility to use lean gases with low caloric value and humid biomass. Since the inverse gas turbine process is a modified gas turbine process, similar to the one used for micro turbines,

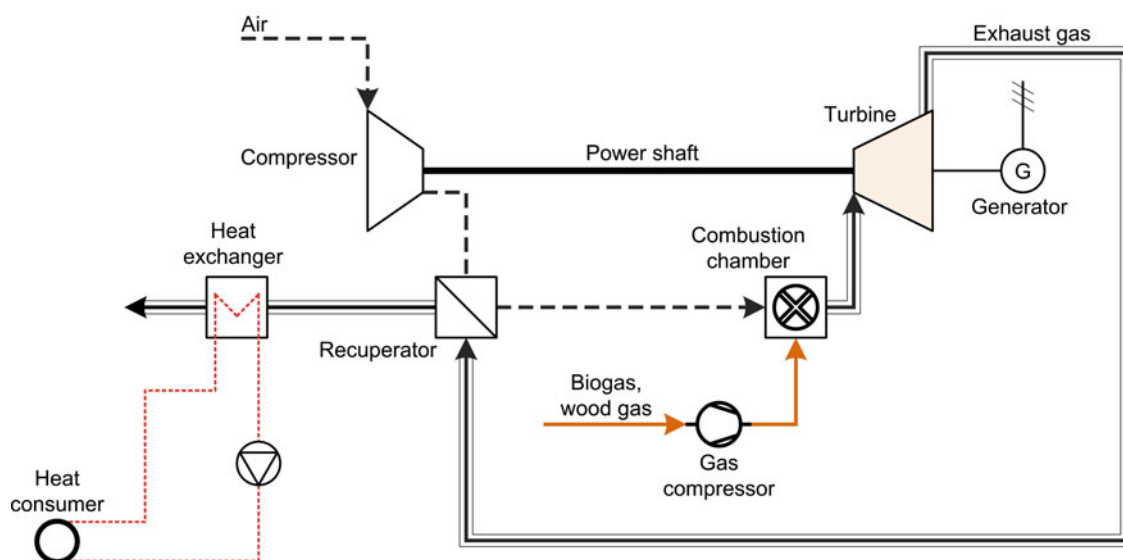
comparable levels of noise emission can be expected. The same applies to the requirement for supporting electric power.

Micro Gas Turbine

Small high-speed gas turbines are referred to as micro gas turbines. The difference between micro gas turbines and conventional gas turbines lies in the power range and the rotation speed.

The combustion air is drawn in through a centrifugal compressor and heated up with the waste heat from the generator, while the generator is cooled at the same time with the cool combustion air. The air heated up this way flows into the combustion chamber, where it is combusted together with the fuel gas. The hot and compressed flue gas expands within the turbine driving the compressor and the generator. The resulting mechanical energy is converted by the generator into electrical energy. In the recuperator, the hot exhaust gases pass on part of their heat to the cooled down combustion air and are discharged from the turbine at a temperature of around 300°C, which can then be used in a downstream heat exchanger to provide process heat (Fig. 16). Micro gas turbines produce high-frequency alternating current of up to 1,600 Hz, which is converted into alternating current with the aid of power electronics [21].

In recent years, natural gas powered micro gas turbines have reached the demonstration and market



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 16

System diagram for a biomass CHP unit with a micro gas turbine [22]

introduction phase and are available in the electrical capacity range of 30–200 kW with efficiency rates of 25–30%. The specific costs for micro gas turbines are between 1,000 and 2,000 € per installed electrical capacity in kW. A positive impact on the cost of modules results from the fact that the cooling of the generator and power electronics can still be performed with air up to an electrical capacity of 60 kW. Only at higher capacity ranges, liquid cooling become necessary. Negative impact on the cost of modules is due to the complexity of the frequency conversion unit and the recuperator. Apart from the cost of modules, additional costs for a gas compressor do usually arise.

The maintenance requirements for micro gas turbines are lower than those for piston engines since there are mostly rotating components in the system. Aero-static bearings used by some manufacturers lead to a further reduction in maintenance requirements. The noise level for some market-ready models up to 100 kW is indicated as approximately 65 dB(A) at a distance of 10 m.

Up to now, most manufacturers have approved the use of landfill gas, sewage gas, and biogas at calorific values between 3.6 and 11.7 kWh/mN³ [23]. Current research is looking into the development of fuelling

systems that allow stable and low emission combustion of gases with low calorific and heating values [24].

Fuel Cell

Fuel cells are one of the future technologies with a high potential of efficiency. In contrast to the thermal power engines, the maximum achievable electric efficiency is not limited by the Carnot limit. For this reason they can achieve substantially higher electric efficiencies than traditional technologies (for this scale up to 45%) with extremely low noise and pollutant gas emissions. The working principle of the fuel cell corresponds to a reversal of water electrolysis, i.e., oxygen and hydrogen react in the fuel cell to form water under release of electrical and thermal energy. Depending on operating temperature and the electrolyte used one can distinguish between different types of electrolyte, all of which are structured similarly.

Fuel cells consist of two electrodes (anode and cathode) separated by a semipermeable membrane. The electrodes are connected to each other through an external electric circuit and thus allow for the flow of electric power to the consumer connected. Since the maximum current of individual cells is limited, technically usable currents are generated through the interconnection of

several single cells into so-called stacks. The electrolyte facilitates the exchange of ions, is impermeable and controls the type of ions exchanged. The choice of electrolyte determines the operating temperature and type of gaseous fuels, which may be used, and thus the areas of application. For the development of new fuel cells as a component of CHP plants, the majority of potential manufacturers opt for PEM technology (polymer electrolyte membrane fuel cell) or the SOFC technology (solid oxide fuel cell).

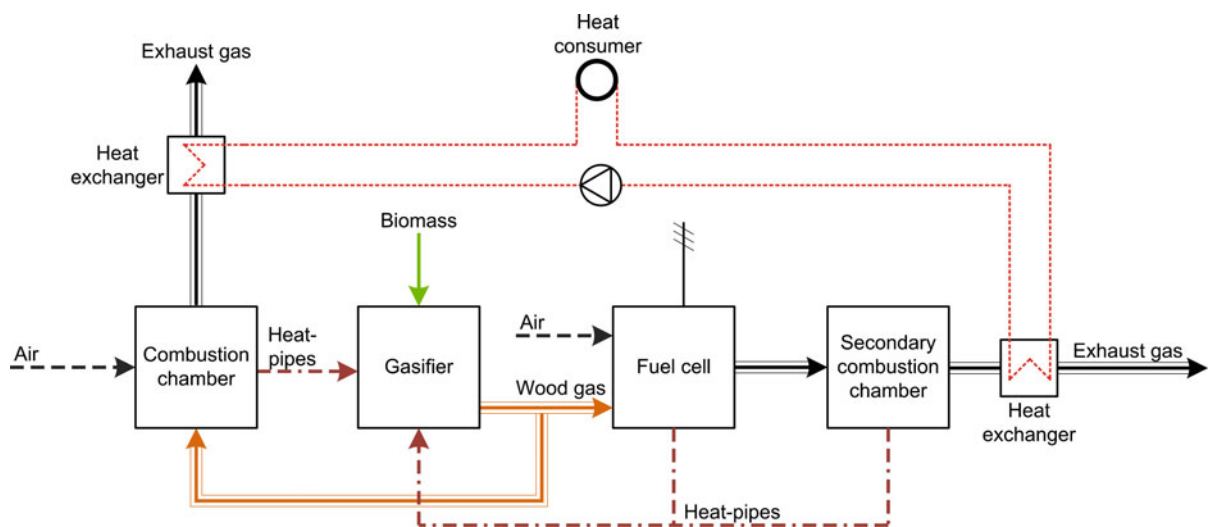
Depending on the electrolyte used, the range of temperature and the number of stacks outputs of a few kilowatts up to several megawatts can be achieved in fuel cell systems. The electrical efficiency is typically between 25% and 45%. For small-scale decentralized plants, performance rates of 30–35% of electrical energy referred to the used primary energy can be considered as being realistic. Due to the modular structure of the stacks, fuel cells generally demonstrate good control properties and low maintenance requirements. Problem areas still remain the comparatively limited operational experience, the long heat-up period for high-temperature fuel cells, the pending proof of long-term reliability as well as the rather high specific costs [13].

Due to the higher operating temperature of SOFC systems, these are less susceptible to the quality of the fuel gases used. However, for PEM systems this means

that the hydrogen required needs to be produced in an upstream reformer and that only high-purity gases may be used. SOFC systems on the other hand are capable of producing hydrogen through an internal reforming process. Hence, high-temperature fuel cells have been identified as better suited for biofuels. For reasons of long-term reliability, sulfur and halogen compounds should essentially be reduced to minimal proportions.

Fuel cell systems could use a wide range of different biofuels. Demonstration projects have been running with biofuels from gasification, landfill, and anaerobic digestion plant. Liquid biofuels, like methanol, ethanol, and dimethylether could also be used. However, presently biogas is the best biofuel for high-temperature fuel cells.

The areas of application for product gases retrieved from solid biomass in SOFC systems have not been explored sufficiently yet. The evaluation of initial research projects however already shows that SOFC systems can generally speaking also be operated using lean gas [25]. Initial trials for the integration of SOFC systems into an allotherm working biomass gasification system have shown that by the use of the TopCycle Process electrical efficiency rates of approximately 43% can be achieved. In application of this principle, the waste heat of the fuel cell is being used as a source of heat for the endothermic gasification process (Fig. 17).



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 17

System diagram for a biomass CHP unit with fuel cell and TopCycle-System (According to [12, 25])

Through this recycling of waste heat into the gasifier it is possible to achieve a net electric power output of approximately 48 kW derived from a combustion heat output of 113 kW [26]. Based on biomass, this option is still within the R&D-status.

Thermoelectric Generator

Thermoelectric generators are construction elements using the “Seebeck effect” to convert thermal energy supplies into electric power. The working principle corresponds to that of a thermocouple. Figure 18 illustrates the relevant system structure. Through the use of p- and n-type-semiconductor legs, with thermal parallel connection, an electrical serial connection is created.

The rate of efficiency and the performance of thermoelectric generators depend, in addition to the material properties, on the number of interconnected pairs of legs and the difference in temperature between the source of heat and the heat sink. The greater the difference in temperature between the warm and the cold side, the higher the efficiency and the rate of electrical output. However, the two temperature levels may not be chosen arbitrarily. On the warm side, 250°C should not be exceeded – for reasons of material resilience – and on the cold side, the lower temperature range is determined by the temperature of the heating cycle. Due to the lower level of temperatures and flow of heat, the rate of electrical efficiency performance decreases 5–6% in the partial load area. In the future, it might be possible to realize results of 10% and above [28].

A major advantage of this technology is the omission of moving parts, which reduces maintenance and operational demands and results in noise-free operation. Thermoelectric generators are therefore suitable for use in pellet-burning stoves installed in living areas. An additional advantage is that no electrical support power is required.

Due to their homogeneous properties, only wood pellets can be used at the moment. Theoretically, one can consider using any other solid biogenic fuel for the supply of heat; however, with the use of inhomogeneous fuels increasing problems can be expected as a result of fluctuating combustion temperatures and residual ash deposits.

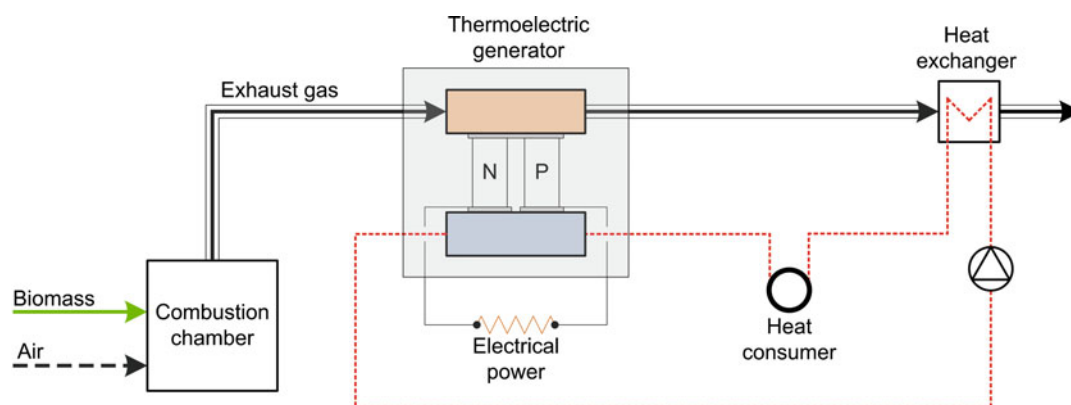
At present the electrical efficiency performance still remains in the rather low range of 400 W, with an efficiency of 2%. For the future a doubling of both these values is aimed [27, 29]. Therefore this option is still within the R&D-status.

Market Survey

Based on the technologies outlined above, the status of these technologies within the bioenergy market is assessed below.

Market-Ready Plants

Gaseous Biomass At present the use of biogas is the most popular renewable fuel for micro cogeneration. Due to a long experience in the use of fossil fuels often standard car engines with necessary technical adaptations



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 18

Schematic design of a biomass CHP plant with thermoelectric generator (According to [27])

are used. The second important technology for this scale and application is the micro gas turbine. The internal combustion engine is more frequently used than the gas turbine because of its long time experience, large production and service infrastructure, and the generally lower power generation costs. Both technologies are suitable for flexible deployment in synchronized to the grid, isolated, and emergency operation.

Despite these advantages, a further increase in the importance of biogas CHP units in private households or small business and community facilities needs a major improvement in biogas fuel production and supply.

There are several manufacturers offering biogas-fuelled motor CHP units for this scale. Below, some interesting units are shown.

The Italian company *Energia Nova* produces micro CHP units with an electric capacity of 20 kW and a thermal capacity of 44 kW based on a 1,200 cc car engine. The electrical efficiency is specified to be at 29% [10]. Also, the company *Tedom* which is based in the Czech Republic offers biogas-fuelled micro CHP units. The smallest available unit has an electric capacity of 28 kW with a thermal capacity of 50 kW. The unit is driven by the gas combustion engine V3800 and has an electrical efficiency of 30% and a thermal efficiency of 53% [30]. *Spilling*, from Germany, manufactures units with an electric capacity between 5 and 20 kW and a thermal capacity between 10 and 43 kW. The overall efficiency is specified to be at ~90%, depending on the return temperature. The specific investment cost of one unit amount to approximately 2,100 €/kW [31].

The American company *Capstone* offers the only on the market available micro gas turbine with electrical capacities below 50 kW. According to its own information, Capstone has around 5,000 plants installed worldwide [32, 33]. The Capstone models are compact design micro turbines with all rotating parts connected to a single shaft fitted with aerostatic bearings. Due to the air bearings technology employed no lubricants or coolants are required. The turbines are fitted with synchronization equipment, which allows for direct connection to the public grid. The internal controls allow for the parallel operation of up to 20 turbines via a central control centre.

Liquid Biomass The use of liquid biomass for energy has become more popular during the last years. For the combined generation of heat and power, typically the

same technologies as for the gaseous biomass are used. Due to the chemical composition of liquid biomass, there are units that cannot work with liquid biofuels directly. Other restraints result from the fuel price, which was very volatile during the last years as well as from the public discussion about the competition with the resource efficiency and the sustainability of liquid biofuels.

One of the major manufacturers of micro CHP units for the use with liquid biofuels in Europe is *SenerTec* from Germany. The 580 cc combustion engine can be used with biodiesel and with rapeseed oil. According to the manufacturers information the electric capacity of the unit is around 5 kW, with a thermal capacity of up to 11.7 kW. The overall efficiency is stated to be at 89% (with an electric efficiency of 29%). The unit works synchronized to the grid and is designed for heat-controlled operation. They reach a maximum flow temperature of 83°C. Through this capability, usage from private households up to small business and community facilities is possible [34]. The investment cost is stated to be at 20,500 € (without value-added tax). The costs will increase for the additional offered accessories (e.g., maintenance kits, condensate pumps, heating circuit distributor). The inspection is done according to maintenance plans and is shortened to 1,400 h when using regenerative biofuels [35].

Other manufacturers are *Cogengreen* from Belgium and *KW-Energetechnik* from Germany.

Solid Biomass At present there are no market-ready micro cogeneration units available operating on the basis of solid biofuels. The around 500 micro cogeneration units so far installed in Europe are primarily pilot and demonstration plants or preproduction series installations with customers. The development of market-ready small-scale biomass gasification plants could be a major step toward a considerable market position of solid biomass-driven micro cogeneration units.

Gasification technology offers a number of advantages in the use of biogenic solid fuels – compared to classical combustion. One essential advantage is the fabrication of a specific gaseous product with properties depending primarily on the production process and only secondarily on the type of biomass used. A high level of efficiency can generally be achieved by integration of gasification into the cogeneration process through combustion engines in the segment of

small- and medium-size capacities. For the thermal capacities applied here, only fixed bed gasification technologies are used.

Generally speaking, fixed bed gasification furnaces based on the co-current or counter-current principle are used in the lower capacity range, due to simpler technology. In the counter-current principle the fuel is supplied from above, whereas the gasification medium is injected from below. In the co-current principle, by contrast the fuel and gasification medium are supplied together from above with falling gasification direction.

A successful market introduction of CHP fixed bed gasification plants in the lower capacity range is being hindered by presently still existing significant technical problems. The main ones include relatively low grades of efficiency, often unreliable operating performance of plants due to technological insufficiencies, usually too high emission levels of contaminants, in many cases insufficient purification of gas as well as the sometimes permanent need for control and frequent technical servicing [36].

Demonstration and Pilot Plants

Like described above, there are many liquid or gaseous biofuel-driven micro CHP units with high electrical efficiency commercially available. Due to this situation, there is a considerably lower need for the development of new technologies. The major parts of the research and development activities are invested in systematic improvement of existing systems. The situation is different at the field of micro CHP units based on solid biomass, where the market-ready units are missing but development approaches for almost every conversion technology exist.

Therefore, some important demonstration and pilot plants based on solid biomass are presented below. This selection is realized with the goal to give an overview of the broad variety of the ongoing activities within this area. The order of the listing corresponds approximately with the status of development.

Hoval (1 kW): Stirling Engine Hoval develops biomass powered small-scale CHP plants in which through a combination of a stirling engine and a firewood powered furnace electrical and thermal energy is supplied simultaneously. Since the autumn of 2008, Hoval is offering an initial small run series with 20 CHP plants. The

rated thermal output of the logwood-burning furnace AgroLyt is 25 kW, the electrical output rating of the stirling engine is 1 kW (with an electrical efficiency of the stirling engine of around 15–20%). A logwood-burning furnace is used to supply the heat required for the operation of the stirling engine. The stirling engine, as a beta-type (i.e., 2-pistons 1-cylinder system), has been designed with an external regenerator and uses nitrogen with approximately 12 bar as working gas.

For retrofitting of an existing wood burning furnace, the door to the combustion chamber needs to be replaced by a door adapted to the stirling engine (Fig. 19). This way it becomes possible to slide the engine inside the combustion chamber. For the optimal channeling of the exhaust gases through the heat exchanger some of the stone lining inside the combustion chamber needs to be exchanged and the control software needs to be adapted for operation of the stirling engine. Through the use of the stirling engine the space requirements of the biomass furnace increase. Apart from the space required for the furnace and the engine installed, additional space is needed for the installation of a track system. This is necessary since the engine has to be pulled out of the combustion chamber far enough so that the door can be opened without difficulties, in order to allow maintenance works on the furnace. Apart from this track system, a system fixing the engine inside the furnace also is necessary [37, 38].

Since an as effective as possible cooling system for the stirling engine is required in order to achieve a high degree of electrical efficiency, the engine is connected to the existing heating system via a separate cooling circuit. Options are, for example, the integration into the return flow of a low-temperature heating system or a connection to a hot water boiler or buffer. Important for all concepts are that optimal cooling of the stirling engine can be ensured. If this is not the case, suitable heat exchangers need to be installed. The electrical connection can be made through integration into a control cabinet [37].

In the course of the optimization phases carried out to date, many of the original operational problems of the plant have been solved. These concern among others the increase of the availability, the electrical efficiency performance, and the electrical capacity of the stirling engine, as well as a reduction in the demand



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 19

Stirling engine mounted in the wood burning furnace (Copyright by Hoval)

for supporting electrical power and an improvement in the overall performance rating of the plant. The investment cost of a stirling engine (together with the required fittings and the control cabinet) amount to approximately 8,000 € [38].

Plans for the further development of the stirling engine include an increase in electrical output to 3 kW as well as an integration of the engine into a pellet boiler with greater thermal capacities, starting at around 50 kW [38].

Stirling Danmark (9 and 35 kW_{el}): Stirling Engine

Stirling Danmark currently offers two plants for combined heat and power generation. A stirling engine of the type SD3 with an electrical net output rating of 35 kW and an electrical efficiency of approximately 27% (according to manufacturers' specifications) is used for the generation of electric power.

In one of the models on offer, a counter-current gasifier produces a combustible gas, which is burnt in a specially designed combustion chamber. The stirling engine in this case is integrated into the combustion chamber. The gasifier is charged from below with

a mixture of air and flue gas recaptured from the combustion chamber and from above with the fuel (according to the manufacturers data wood chips with a humidity level of up to 55%). Cleaning and reprocessing of the exhaust gas is not provided in this concept. The usable thermal output stands at approximately 145 kW, with a thermal fuel input value of 200 kW [39].

In addition there is another model where the stirling engine is fitted inside the combustion chamber of a wood chips burning furnace. In order to increase the performance rate of the stirling engine the combustion air is already preheated to around 250°C. Using wood chips with a humidity level of up to 50%, a thermal capacity of 215 kW and an electrical efficiency of 35 kW can be supplied by a thermal input rate of 290 kW [40].

Apart from the CHP unit rated at 35 kW electrical capacity Stirling DK is also developing a small-scale CHP plant. The core section of this plant is a beta-stirling engine with an electrical output of 9 kW which, according to the manufacturers, should reach an electrical efficiency rate of approximately 28% [41].

Talbott's (25 kW_{el}): Hot-Air Turbine The company Talbott's Biomass Energy Group Ltd. supplies CHP plants with electrical output ratings ranging from 25 kW up to 100 kW. The humidity levels of the fuels used should not exceed 25%; however, operation at humidity levels up to 40% is possible, in principle. Through the separation of the hot-air turbine process from the supply of heat the operation of furnace and turbine can largely be optimized independent of each other.

The combustion takes place in a stepped grate with automatic ash removal and the plant can be operated with wood chips of G50 quality or wood pellets. A hot-air turbine is used for the generation of electric power, with a manufacturer stated electrical efficiency rate of 20%. The price per installed electrical capacity for the CHP plant is between 6,200 and 8,800 €/kW [42].

Sunmachine (3 kW_{el}): Stirling Engine Sunmachine has also been working for a number of years on the development of a micro cogeneration unit for domestic use as well as small-scale commercial objects. According to manufacturers information, the grid feed-in capacity of the CHP plant ranges from 1.5 to 3 kW, with electrical efficiencies of 20–25%. The thermal capacity is stated as 4.5–10.5 kW. Wood pellets are listed as suitable fuel. The cost per installed electrical capacity of the CHP plant (excluding heat storage, connection, etc.) is around 7,600 €/kW.

Due to governmental subsidies in Germany and the interest in the technological concept, of combining a compact upside-down burner with a newly developed stirling engine, some 400 plants have been sold and installed to date [43]. Partly responsible for the considerable shortfall in meeting the original sales targets is an underestimation of the need for further operational optimization in practice applications. Following restructuring measures (at the end of 2009) and a major reduction in production volumes, resumption of normal production can be expected only once the still remaining technical problems have been solved.

Cleanergy (7.5 kW_{el}): Stirling Engine Already in June 2007, the company SOLO Stirling (the original

developer of the stirling engine type V161) had to file for insolvency. The company was subsequently taken over by Stirling Systems and renamed as Stirling Systems. After this company, as well, had meanwhile filed for insolvency, the technical know-how was acquired by the Swedish company Cleanergy. According to a company statement (at the end of 2009), Cleanergy intends to resume production of the stirling engine by 2010 at the latest.

SOLO Stirling had started with the series production of the model V161 in 2002 and had sold around 150 units since the original market launch. Besides the original concept, in which natural gas is used as fuel, tests were also made with the use of biomass. In this context, the direct supply of heat through the combustion of biomass had been investigated, as well as the use of wood gasifier. In operations with a fixed bed counter flow gasifier, the stirling engine V161 achieved an electrical output rating of between 2 and 7.5 kW with a thermal output 8 to 22 kW (i.e., electrical efficiency of around 20%) [41]. It is presently not known whether Cleanergy intends to further pursue the development of a model using biomass.

Bioenergy 2020+ (0.2 kW_{el}): Thermoelectric Generator Austrian Bioenergy Centre (now Bioenergy 2020+) has been exploring the technical viability of using the “Seebeck effect” for the cogeneration of heat and power with a pilot plant since 2006. The objective of the project is to use a modern pellet furnace in isolated operation, regardless of the availability of electric power supplies. As a result of these parameters, the plant is operated in a heat-controlled mode with low electrical output of the power generating unit.

The thermoelectric generator TEG 250 consist of 16 interconnected modules with altogether 288 pairs of legs. In the initial development phase, the thermoelectric generator with an electrical output of 200 W was integrated into a standard wood pellet furnace. The objective was to demonstrate the practical implementation of this combination and to investigate whether the potentials worked out in theory could actually be achieved in practice. During the initial trials, electrical efficiencies of 4% for the generator and 2% for the system as a whole were achieved. As a next step,

the still remaining measures for optimization are to be implemented (e.g., optimizing the heat transfer process, reducing the risk of overheating, ensuring stable, and complete combustion); and the electrical performance of the generator is to be doubled, while reducing the costs by half at the same time [29].

OTAG (3 kW_{el}): Steam Piston Engine Another development is the “lion-Powerblock” from OTAG. Based on the already available natural gas fired “lion” OTAG has been working (since 2007) on a combination suitable for practical application of the “lion-Powerblock” with a wood pellet furnace.

Basis for this is the Linator® – a free-moving piston in a closed process steam operation. The hot gases from the combustion process are used to produce process steam with a temperature of approximately 350°C and a pressure of 5–30 bar. The steam cycle, as is customary for steam piston engines, is a closed system with external combustion.

According to the manufacturers’ information, the first plant is undergoing field-testing in monovalent operation since the autumn of 2009. The thermal output modulates in a range between 4 and 14 kW, with an electrical output rating of 3 kW.

Aactor !GT – Ökozentrum Langenbruck (9 kW_{el}): Inverse Gas Turbine Until the end of 2009, the Ökozentrum Langenbruck had been working on the development of a prototype model for an inverse micro gas turbine with a feed-in capacity of approximately 2.4 kW that was to serve as the basis for the design of a prototype turbine powered by atmospherically combusted lean gas. Decisive for the decision to develop such a plant were the results of a market and technology analysis made by the Ökozentrum in which inverse gas turbines were identified as a robust and economically viable technology for the use of lean gases.

Since the first two project phases went rather promisingly, a prototype suitable for field-testing is now to be developed in the next project phase and ultimately the prototype for a lean gas powered inverse gas turbine with a feed-in capacity of 9 kW [19].

Conclusions

Below some conclusions are drawn.

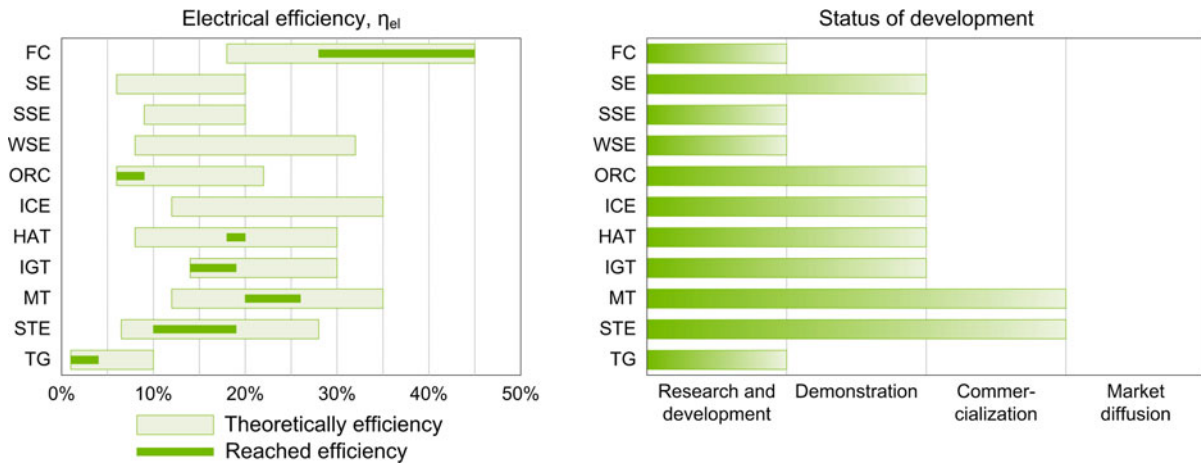
Technological Aspects

The rate of electrical efficiency is one of the main indicators for the evaluation of small-scale CHP plants. This is due to the fact that the economic advantage gained through the feed-in of electricity into the grid and the resulting reimbursement – or through a reduction of the electric energy consumption brought from external sources – generally tend to be significantly higher than those potentially to be gained by the provision of heat.

Below the theoretical electric efficiency together with the current status of development is shown for the conversion technologies and the capacity range described above (Fig. 20). A comparison of these two charts highlights one of the key problems of the use of biofuels for micro cogeneration in general and solid biofuels in particular. On the one hand, the theoretical efficiency potential of most of these technologies is not yet sufficiently exploited. On the other hand, the technology with the highest electrical efficiency rating, (i.e., fuels cells) is currently not available on the market. Applications, on the basis of solid biomass, for the most proven technologies (i.e., steam turbines and micro gas turbines) are presently still missing in the performance range reviewed.

Despite increased research activities over the past few years hardly any commercially operating solid biomass CHP plants can be found up to now in the capacity range under review. An interesting aspect in this context is the fact that two promising developments are not being pursued any further since, from the perspective of the plant manufacturers, an economic operation of the plants is not possible for the time being.

The first of these two is a micro ORC unit with an electric capacity of ~10 kW and a thermal capacity of ~80 kW that was developed by Turboden from Italy. The second one is a four-cylinder stirling engine with an electrical capacity of 1 kW, which uses the hot combustion gases of a wood pellet furnace for the generation of power, developed originally by SPM and later by KWB. After the first plants had already been tested for their practical suitability within a field test, the project was abandoned at the end of 2009. According to statements by KWB it is the presently still rather low actual customer interest that is mainly



Biomass Energy Small-Scale Combined Heat and Power Systems. Figure 20

Electrical efficiency and status of development of examined conversion technologies for the micro cogeneration on the basis of biomass. For technologies with no real electrical efficiency shown assessable projects are missing. (ICE, Internal combustion engine; SE, Steam piston engine; SSE, Steam screw-type engine; STE, Stirling engine; WSE, Water steam engine; ORC, Organic Rankine Cycle; HAT, Hot-air turbine; IGT, Inverse gas turbine; MT, Micro gas turbine; FC, Fuel cell; TG, Thermoelectric generator)

responsible for this decision. The still ongoing field tests will be completed in order to be able to use the experiences gained for later developments [44].

This also leads to the assumption that either the market for solid biomass micro CHP units is not important enough or the still remaining technical problems, at present, do not justify any further intensive development activities.

Table 1 additionally shows the major advantages and drawbacks of the CHP technologies reviewed. The stated values are to be considered as indications only. In the performance range up to an electrical capacity of 50 kW, internal combustion engines together with micro gas turbines currently represent the most advanced technology for the cogeneration of heat and power by the use of liquid or gaseous biofuels. However, up to now only landfill gas, sewage gas, or biogas with a calorific value between 3.5 and 11.7 kWh/m³ may be used as fuel. The use of lean gas is still not possible. For the use of solid biofuels the greatest potential for an introduction to the market, in the medium term, is attributed to the stirling engines as these can be integrated into existing furnaces without major reconstruction measures. Nevertheless, the electrical efficiency rates that can be achieved with this

technology (up to 20%) are rather low and the technology is still not market mature. Any noticeable market penetration by the remaining technologies over the next 5–10 years would seem at least doubtful.

Among the drawbacks hindering market penetration are first of all the high investment costs for CHP plants, due to low numbers and resulting high unit costs, as well as technical problems related to the inhomogeneous structure of biomass and furthermore, in comparison to gas or oil, the high proportion of non-combustible contaminants. This leads to the currently very low operational lifespan of the plants, low electrical efficiencies, frequent servicing intervals, and a high level of maintenance and operating costs.

Potential Fields of Application

Throughout Europe the greatest potential for micro cogeneration plants is seen in buildings with central heating systems. This means that the conventional generator of heat is replaced by the CHP plant. The heat generated is used for space heating, the supply of hot water and cooling systems for buildings, whereas the electric power generated is primarily used to cover own electricity requirements.

Biomass Energy Small-Scale Combined Heat and Power Systems. Table 1 Key characteristics of the biomass CHP technologies investigated

Conversion technology	Main advantage	Main drawbacks
Internal combustion engines	Well established; wide selection of plants on offer; acceptable costs and grades of efficiency	High level of noise; low exhaust gas temperature; gaseous or liquid fuels required
Steam piston engines	Good partial load performance	High level of noise; very high maintenance requirements
Steam screw-type engines	Good partial load performance	Only limited operating experience; high level of noise
Stirling engines	Adaptable to different furnaces (external combustion); low noise level	Low grade of electrical efficiency; high maintenance requirements
Water steam engines	Proven technology in the higher capacity range	High specific costs for smaller capacity range; low grades of efficiency, high level of noise
Organic Rankine Cycle	Lower inlet temperatures can be used; very good partial load performance	Low grades of efficiency (only limited scope for improvement)
Hot-air turbine	High exhaust gas temperature; high degree of efficiency potential with steam injection; simple process	High cost of high-temperature heat exchanger; complexity of plant system
Inverse gas turbine	Good degree of efficiency potential; wide range of fuel sources	Low grades of efficiency; development just starting; complexity of plant system
Micro gas turbines	High exhaust gas temperature; acceptable grades of efficiency possible	Gas compressor required; use of lean gas not yet possible
Fuel cells (SOFC)	Very high grades of electrical efficiency possible; high exhaust gas temperatures; internal reformation	High internal temperatures; problems with reliability/durability of material; long heating up periods; use of lean gas not yet sufficiently tested
Thermoelectric generator	Noise free; low maintenance requirements; no support energy required; black start possible	Very low grades of efficiency

A positive economic effect in this context comes from applications with a year-round constant demand for heat and the resulting increase in full-load operating hours as well as from applications with a high electric base load, which reduce the amount of external electricity supplies to be purchased and at the same time reduce the amount of power produced that has to be fed into the grid, usually at a lower price.

In addition to the high investment costs an economic operation is currently still impaired by comparatively high servicing and maintenance costs for biomass-based systems, the often low electrical efficiencies of less than 20%, and the resulting unfavorable balance between thermal and electrical output (for

biomass micro CHP plants the thermal output is usually greater than the electrical output by a factor of 3.5–10).

Two promising application fields can be distinguished.

Private Household Sector The economic use of micro CHP plants in private households proves to be difficult at the present stage of development despite the high potential for primary energy cost savings. For small single-family dwelling houses, the returns from electricity feed-in or own use are often not sufficient to amortize the high cost of initial investments in the plant.

The heat-controlled operation in combination with increasingly available solar powered hot water supplies often result in full-load operating hours of the CHP plant which allow for the 2,000 h/a to be reached only with the aid of large heat buffers and very low heat output of below 10 kW thermal capacity. An economic operation of a CHP plant will hardly be possible on this basis.

The combined generation of heat and power in single-family dwelling houses is in general economically only viable when the power generated is used to cover own demand, with simultaneous use of the heat. With heat-controlled operation of the plant, the usually rather intermittent demand for heat and in part strongly varying patterns in the demand for heat and power, only a small portion of the own demand for electricity can be covered by micro CHP plants – also as the necessary electric power storage devices are not yet available.

A possible remedy in this respect could be provided by the thermal storage devices available, as a standard, with biomass fuelling and local energy and load management systems. Active load management should be able to offer opportunities to adapt the charging cycle of the heat storage device to the electric load profile in such a way that the CHP plant can produce, if possible, large supplies of electric power during periods of high electric load. Similarly, should the operating periods for major electrical appliances (e.g., washing machines, dryers) be changed in such a way that peak loads do not occur, and that during other times the equipment is operated with otherwise lower electrical and thermal loads, while the heat storage device is being recharged.

In special cases, biomass-based micro CHP in the lower capacity range can already today offer a clear advantage compared to fossil fuel systems. Such applications include, for example, isolated operation in remote regions (e.g., mountain lodges). These often do not have any access to the power grid and as a result often have low electric loads, and due to their location do usually have better access to wood as a fuel than to fossil energy sources. In such cases, a biomass micro CHP designed for isolated operation and without or only low electricity demand offers the possibility for an efficient supply of heat and power.

Small Business and Community Facilities In contrast to single-family dwellings, micro CHP plants can be operated significantly more economically in small manufacturing businesses and office buildings as well as in community objects, such as administrative offices, due to an overall greater supply and often the possibility of being able to significantly better predict the demand for heat and power. Beside the demand profile for heat – which should be evenly distributed over the year, if possible – the demand profile for electric power plays a key role in the evaluation of micro CHP plants under these conditions. Applications with a largely simultaneous demand for heat and power are suitable for cogeneration just as much as those, where the CHP plant can be used to cover the electric base load. The most suitable applications include:

- Community facilities (administration buildings; swimming pools; hospitals)
- Industry and commercial buildings (hotels; office buildings; small supermarkets)

Future Directions

Technologically. In order to be able to capture the existing market potential, the present-day concepts for micro cogeneration need to be further developed in some essential points. In general, developments are required in the electrical output range of 0.5–2 kW, 5–10 kW, and 20–50 kW in order to be able to respond to the different profiles in the demand for heat energy (households, small multiple housing units and small public buildings, medium-sized and larger public and social institutions, as well as small- and medium-sized enterprises).

A high degree of reliability with low maintenance costs is required for all applications. Especially in the two lower performance ranges should servicing be required only once a year (as a maximum) and operations should be running fully automatic. More frequent servicing and controls for larger plants are possible provided if they result in limited work and, most importantly, limited costs. All concepts should be designed in such a way that heat can be provided independent of the supply of power. As the systems are in general operated heat controlled – and only a charging period for the heat storage device can be

stipulated – any additional costs in comparison to a pure heat generator must be limited. Correspondingly, the specific costs per kW thermal energy should only increase (as a maximum) by the amount of savings achieved in the cost of electricity supplies.

For the installation in residential buildings, it is mandatory to provide for a sound-insulation casing and the overall system should be designed in such a way that it requires as little space as possible (including fuel storage), and it should be easy connectable to the existing domestic network (in particular connection to an existing buffer system, with or without solar system). In order to ensure optimal operation – even more so than in the case of biomass furnaces – attention needs to be paid to optimizing controls, including coordination of demand and operating periods of the plant. Subject to these preconditions, micro CHP plants powered by solid biofuels can and will gain in importance in the future – initially only in niche sectors, but with rising costs of energy later on also more widely.

Biofuels. A high tolerance for the quality of the biomass in use is one of the major factors for the future relevance of biomass for micro cogeneration. Systems with high requirements on fuel quality, like it is common for the use of solid biomass, will primarily be established in Central Europe and maybe Northern America. For the remaining regions, the establishment of a market for these fuels is at least very doubtful.

Technologies that could be used with locally available fuels seem to have the greater global potential for decentralized biomass-driven micro cogeneration. Therefore, systems consisting of a conversion stage, in which a fuel gas is produced, and a subsequent use of the gas in the cogeneration unit appear best suited for this. According to the actual stage of deployment, micro anaerobic digestion, and micro gasification could play a particular role in the production of the fuel gas. Ligneous biomass as well as organic waste can be used as raw materials. The combined generation of heat and power can take place in a downstream micro CHP unit. All the technologies mentioned in the section “[Market survey](#)” will be usable for this purpose. Due to existing long time experience, large production and service infrastructure and the generally lower specific costs internal combustion engines and micro gas turbines have clear advantages.

Building automation. The future spread of biomass micro CHP plants can be further supported by the increased use of active systems for building automation. In combination with suitable heat storage devices, active systems for building automation allow a power-controlled operation of the CHP plant just as well as electricity storage devices allows a thermal-controlled operation. Both approaches offer the greatest possible reduction in the amount of electricity that needs to be fed into or taken out of the grid.

Such systems – in the course of pending refurbishment measures – can however be retrofitted together with all the associated effects on existing electrical equipment and the building’s power supply, particularly in the case of larger buildings. The integration into existing single-family dwelling houses will rather be the exception. Ideally these systems should be taken into consideration already at the planning stage.

Economically. Independent of the political measures taken to improve the economic viability of mini-CHP plants compared with other options, the investment costs for cogeneration units have to decrease substantially, while servicing intervals have to be lengthened significantly also to lower ongoing operating costs. In particular, for plants in which biomass is used the still rather high specific costs and short servicing intervals do obstruct any noticeable market penetration. The high costs and resulting long amortization periods do represent a major obstacle, especially for the private sector.

Politically. In order to achieve the stated climate protection targets, the further development of mini-CHP plants is supported through governmental support programs – at least in European countries that are considered to be the driving force for decentralized cogeneration of heat and power in the lower performance ranges. In Germany a bonus of 0.0511 €/kWh is granted for all electricity produced through cogeneration, and therefore also for the proportion used to cover own demand. Similar programs can currently be found in Great Britain and in The Netherlands. However, the market development during recent years have shown that the market for mini-CHP plants presently still depends on political support; for example, in Germany between autumn 2008 and the end of 2009 approximately 7,000 new mini-CHP plants were installed – following discontinuation of the subsidy program it came to a massive reduction in the number of newly installed units.

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Biomass Gasification for Electricity and Fuels, Large Scale

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Article Outline

Glossary
 Definition of the Subject
 Introduction
 Gasification: Principles

Suitable Types of Gasifiers
 Producer Gas Composition
 Options to Use the Producer Gas
 Future Directions
 Bibliography

Glossary

- AER** Adsorption enhanced reforming, dual fluidized bed gasification process for generation of producer gas with high hydrogen content.
- Allothermal gasification** Heat necessary for the gasification process is generated externally and delivered to the gasifier by a heat exchanger or a heat carrier media.
- ASF** Anderson Schultz Flory distribution, mathematical model for Fischer Tropsch product distribution.
- Autothermal gasification** Heat necessary for the gasification process is generated in the same reaction chamber where the gasification reactions take place.
- Biofuel** Solid biogeneous material used as feed for gasification or fuel for transportation with biogeneous origin.
- CHP** Technology for combined heat and power production.
- CV** Calorific value, energy content of a fuel given in MJ/kg or MJ/m³.
- DME** Dimethylether, proposed gaseous biofuels for transportation.
- Fuel oriented** Process for maximizing fuel production.
- FT** Fischer–Tropsch, synthesis reaction proposed for the production of liquid biofuels.
- IGCC** Integrated gasification combined cycle, process for maximized electricity production via gasification.
- Large scale** Large scale refers here to gasification plants with capacities larger than 10 MW fuel input and able to be up-scaled up to or above 100 MW fuel input.
- ORC** Organic Rankine Cycle, process for electricity production from heat.
- Polygeneration** Process for generation of at least three different products in one plant at the same time, e.g., heat, electricity, and biofuels.
- Producer gas** Gas produced in a gasification process.

R&D&D Research and development and demonstration.

SNG Synthetic natural gas, gas produced from solid biomass via gasification with a quality comparable with natural gas.

Syngas (synthesis gas) Producer gas upgraded for synthesis processes.

Synthetic Produced by synthesis reactions.

Synthetic biofuel Biofuel for transportation purpose produced via gasification followed by synthesis processes.

Definition of the Subject

It is commonly agreed that gasification of biomass has a large potential for a more sustainable energy system in the future. However, a lot of research and demonstration efforts have been carried out during the last three decades but there are only a few gasification technologies which are available commercially at the market so far. In the 1980s and 1990s CHP (combined heat and power) production based on gasification has been investigated intensively and several different technologies have been demonstrated in an industrial scale. In the last decade, research and development in biomass gasification have been focused mainly on the production, cleaning, and upgrading of producer gas to synthesis gas (syngas) quality and several synthesis reactions have been studied especially those leading to biofuels for the transportation sector.

This paper gives an overview about the state of development for large-scale biomass gasification and applications of the producer gas for electricity and/or biofuels production. Small-scale gasification is not tackled in this contribution. Large scale refers here to gasification plants with capacities larger than 10 MW fuel input and able to be up-scaled up to or above 100 MW fuel input. In this scale plants for electricity production can be considered as commercially available whereas technologies for biofuels production are still under development or demonstration.

Starting with fundamentals of biomass gasification and basic definitions gasification reactors for biomass proposed or used so far for large scale are described and characterized briefly. The resulting producer gas composition depends on a lot of parameters, therefore, the gas composition of only the most frequently utilized

gasifier configurations are discussed. These configurations cover more or less the whole range of gas composition of the different gasifiers used so far. Gas cleaning as a crucial part in each process based on biomass gasification is dealt together with typical applications for electricity or biofuels production. It is neither possible nor useful to describe all configurations which can be found in literature. Therefore, the available information is summarized and typical gas cleaning strategies are presented. Finally, the most important synthesis reactions are described and complex biofuel production routes are shown. These processes are based mainly on catalytic reactions at elevated pressures and temperatures. The requirements for syngas are extreme especially in terms of sulfur contents as these substances are poisons for most of the catalysts used. Furthermore, hydrogen to carbon monoxide ratio has to be in a certain range in order to get high yields of the desired products.

Two different strategies can be followed for biofuels production: fuel orientation or polygeneration. Fuel orientation means to optimize the process for maximizing the yield of biofuels. Polygeneration means the production of at least three different products, normally in case of gasification heat, electricity, and biofuels.

Introduction

In the 1980s and 1990s combined heat and power (CHP) production was the main technology which has been investigated and a lot of different demonstration plants were built and operated [1–3]. A lot of experience could be gained during this time and several plants are able to reach availabilities up to 90%. One of these successful technologies is the dual fluidized bed gasifier which was demonstrated for the first time in Güssing/Austria and is now realized in several other industrial plants at a scale of 10–25 MW fuel input in Austria and Germany [4, 5]. The main obstacles for a broad commercialization are still the lack of sufficient experience and several “negative examples” in the last years. Therefore, for electricity generation, there is still the problem to show a real economic advantage compared with combustion-based technologies for potential investors like, for example, energy utilities.

During the last years R&D efforts have been directed more and more toward synthesis gas (syngas) production from biomass via gasification. Syngas consists mainly of hydrogen and carbon monoxide and is used to produce synthetic materials such as synthetic biofuels. Contrary to CHP, there is no competition with combustion technologies (e.g., production of Fischer–Tropsch fuels) and the market introduction is expected to be much easier. The most advanced and intensively investigated biofuel syntheses are Fischer–Tropsch (FT) synthesis, methanol synthesis, and mixed alcohol synthesis, leading to liquid biofuels. Additionally, synthesis processes leading to synthetic natural gas (SNG) and dimethylether (DME) and thus resulting in a gaseous product are also under intensive investigation. Recently, the first demonstration plant for SNG-production from biomass went into operation in Güssing, Austria.

Figure 1 shows a general process flow sheet for the possibilities of producer gas or syngas utilization. The simplest case is the combustion of producer gas for industrial heat or for co-firing as nearly no producer gas cleaning or upgrading is necessary. Most applications try to produce combined heat and power where a tar and particle reduction has to be foreseen. The production of synthetic products requires a specific gas composition (e.g., hydrogen to carbon monoxide ratio) and an ultra clean gas. Therefore, an extensive gas cleaning and gas upgrading is necessary in most of these cases.

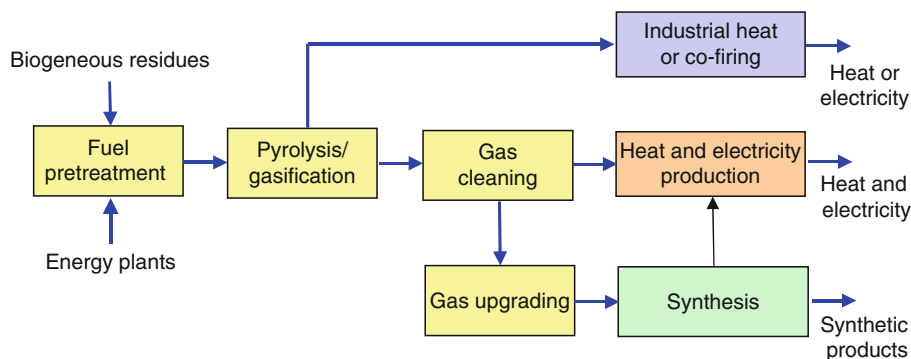
Instead of the generation of single products from producer gas combinations of different products are the more promising way for future applications. Due to the fact that CHP (combined heat and power) production is already established, the combined production of heat, power, and even one or more synthetic products are under development. Such concepts are called polygeneration or also biorefineries. The gasification is the key technology for these concepts.

Gasification: Principles

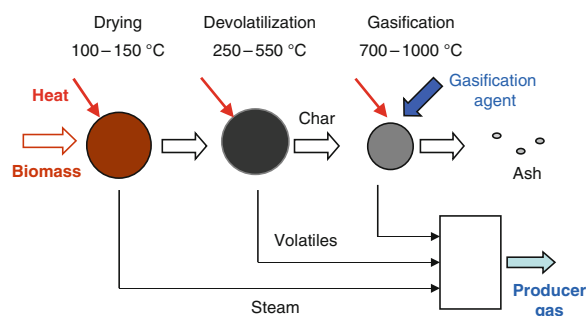
Much work has been published in this field, and a lot of information is available in numerous books and journal papers [3–5, 10, 12]. Therefore, a short summary of the most important principles is presented below to give a review of the current state of the art on gasification reactions and reactor design.

Figure 2 shows the processes which a biomass particle undergoes during gasification. All steps such as drying, devolatilization, and also gasification of the remaining char are endothermic reaction and, therefore, heat has to be supplied to make them running. Another important fact which has to be taken into account for the design of gasification reactors is the release of volatiles. About 80% of the weight of biomass is released during devolatilization and only about 20% remains as char. For one particle, all processes are running consecutively and not in parallel.

In case of pyrolysis, the reaction is stopped after devolatilization (Fig. 2). Then three products are



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 1
Possibilities for producer gas utilization



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 2

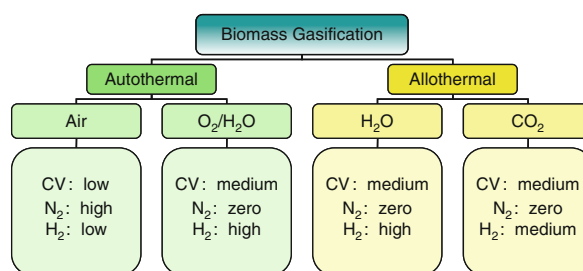
Processes during gasification of a single particle

Biomass Gasification for Electricity and Fuels, Large Scale. Table 1 Gasification agents for char gasification and resulting products

Biomass	Gasification agents	Products
C	$\frac{1}{2}\text{O}_2$	CO
C	H_2O	$\text{CO} + \text{H}_2$
C	CO_2	2CO
C	2H_2	CH_4
C	Air (21% O_2 , 79% N_2)	$\text{CO} + \text{N}_2$

available: char, condensable volatiles (pyrolysis oil), and gases. Such a pyrolysis is well known as own thermal conversion process but also as pretreatment step for gasification. The latter application is even more important as for most large-scale gasification processes based on entrained flow gasification a pyrolysis step is foreseen.

Table 1 contains basic chemical reactions which take place in each gasification reactor in order to gasify the remaining char after devolatilization. By using a specific gasification agent, the producer gas composition can be influenced. But the most commonly used gasification agent in biomass gasification is still air. This means that the producer gas contains a lot of N_2 which is only a dilution as N_2 cannot be used in any of the presently known applications. Other gasification agents – that lead to high-grade producer gas without N_2 – are pure oxygen, steam, carbon dioxide, and hydrogen (see Table 1 or Fig. 3).



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 3

Classification of gasification processes based on heat supply and gasification agents (CV calorific value)

In case of air as gasification agent autothermal gasification is realized. This means that the necessary heat for gasification is produced by partial combustion of the biomass in the same reaction chamber. Another option is a mixture of steam and oxygen to obtain a nitrogen-free producer gas; this possibility is normally applied in large-scale coal gasification (Fig. 3).

To avoid an air separation unit another approach has been established. This process is based on allothermal gasification. This means that the heat necessary for gasification is supplied indirectly via a heat exchanger or a circulating heat carrier. Both types are currently under investigation and also demonstration plants have been built.

In case of poly-generation, the requirements on the syngas quality are defined by the most stringent application. And for the provision of heat, electricity, and biofuels, this is normally the quality defined by the synthesis reactions for the production of biofuels. From such a clean syngas – a mixture of mainly hydrogen and carbon monoxide together with carbon dioxide and other minor components – several interesting synthetic substances can be produced. Currently, the most interesting products are biofuels such as FT-diesel and methanol which are liquid products whereas DME and SNG are gaseous. All four reactions need catalysts which are normally extremely sensible to poisoning, e.g., by sulfur components. Furthermore, the temperatures are in the range of 200–400°C and a pressurized operation is desirable or necessary.

Biomass Gasification for Electricity and Fuels, Large Scale. Table 2 Requirements for syngas

Requirement	Measure
Low content of inert gases (e.g., nitrogen)	Gasification agent steam/oxygen
Optimal H ₂ /CO ratio	Steam gasification (dual fluidized bed)
	Shift reaction downstream
Low tar content	High-temperature gasification
	Tar removal downstream
Mostly, low methane content	High-temperature gasification
	Methane reforming downstream
Low content of catalysts poisons (e.g., sulfur, chlorine)	Removal downstream (Capture in fluidized bed gasifier)
Mostly, medium or high pressure necessary	Pressurized operation mostly beneficial
	Downstream compression

There are a lot of requirements on the composition of the syngas and the impurities. Table 2 contains some of these requirements. First of all inert gases which are not involved in the reactions should be avoided. For example air as gasification agent leads to about 50% of nitrogen in the syngas which is no educt or reaction agent for none of the synthesis reactions. Therefore, steam or oxygen/steam mixtures are preferable gasification agents. Additionally the different synthesis reactions need different stoichiometric H₂ to CO ratios. Even due to the fact that in practice the ratio differs from these stoichiometric values slightly, in any case a certain H₂ to CO ratio is necessary for an optimal operation. Also low tar contents and mostly also low methane contents (exception methanation) are beneficial. The most serious requirements are the avoidance of poisoning of the catalyst due to sulfur or other undesired components in the syngas. For example, sulfur has to be removed from the syngas down to 50 ppb(v) to reach a long-term operation with sufficient high yields of the desired products [8, 9]. Finally, gasification systems which allow pressurized gasification

are well suited for syngas production as almost all synthesis reactions are operated under pressure. An alternative way to the last requirement is a downstream compression of the gas.

Suitable Types of Gasifiers

After definition of requirements for a well-composed producer gas, different types of gasifiers are presented that have been used or currently under development and demonstration for biomass gasification. Gasifiers are normally classified based on fluid mechanic properties in fixed bed, fluidized bed, and entrained flow gasifiers [10]. This classification is used here too. As producer gas from air-blown gasifiers is not suitable for syngas production, these gasifiers are not discussed in detail below.

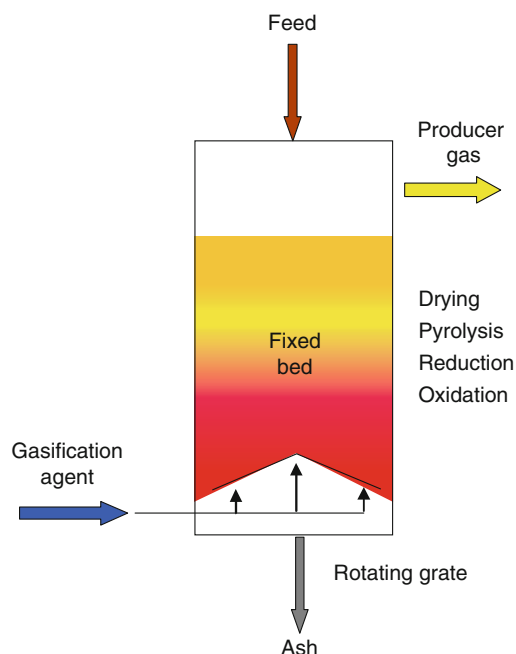
Fixed Bed Gasifiers

Fixed bed gasifiers are used for producer gas generation from coal, e.g., at Sasol, South Africa. Furthermore, fixed bed gasifiers were also operated at “Schwarze Pumpe,” Germany, for gasifying waste. These gasifiers have been shut down recently but a lot of experience is available from the operation over many years.

A schematic figure of a typical fixed gasifier can be seen in Fig. 4. For large-scale gasifiers only an updraft operation has been used. The operation in case of “Schwarze Pumpe” can be characterized as follows [12]:

- Solid waste has been used (e.g., plastics, sewage sludge, fluff from cars, paper and industrial plastics, contaminated wood, municipal solid wastes).
- Solid fuel is required in lumpy form (20–80 mm) to facilitate the counter-current flow of rising producer gases and descending solids.
- Briquetting, pelletizing, or further suitable methods of fuel agglomeration are required.
- Internal diameter within the gasifier has been up to 4.0 m.
- Pressurized operation of the gasifier has been realized (e.g., 25 bar).
- A mixture of steam and oxygen has been used as a gasification agent.

Currently, no intensive research and development efforts are carried out in the field of large-scale fixed bed gasifiers for producer gas generation from biomass.



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 4

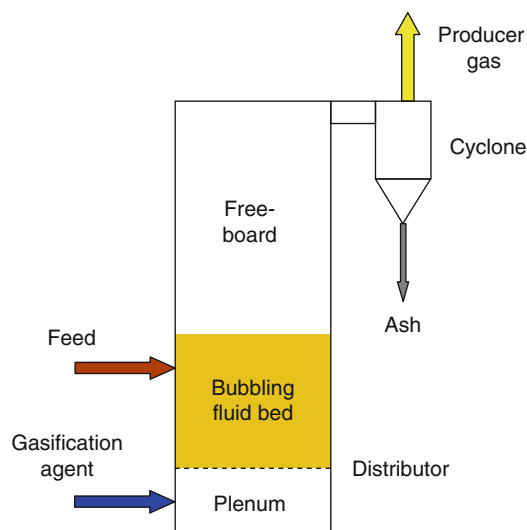
Typical arrangement for fixed bed gasifiers after [12]

Fluidized Bed Gasifiers

For fluidized bed gasifiers, a bed material is used which guarantees a stable fluidization and provides excellent heat and mass transfer conditions. This bed material can have further functions; it can act, e.g., as catalyst for the gasification reactions or as a carrier for, e.g., CO_2 in case of the AER (adsorption enhanced reforming) process. The gas necessary for fluidization serves as gasification agent.

Dependent on superficial gas velocities and bed material diameter two types of fluidized beds are distinguished: stationary (bubbling) and fast (circulating) fluidized beds. By combining two of this fluidized bed types dual fluidized bed configurations can offer further advantages for syngas production [3].

Stationary (bubbling) fluidized beds use bed materials with a mean particle diameter between 0.5 and 1 mm and superficial velocities typically between 1.5 and 2.5 m/s. Bed heights range from 0.5 to 2 m followed by a freeboard with a height of several meters. Steam/oxygen mixtures are used as



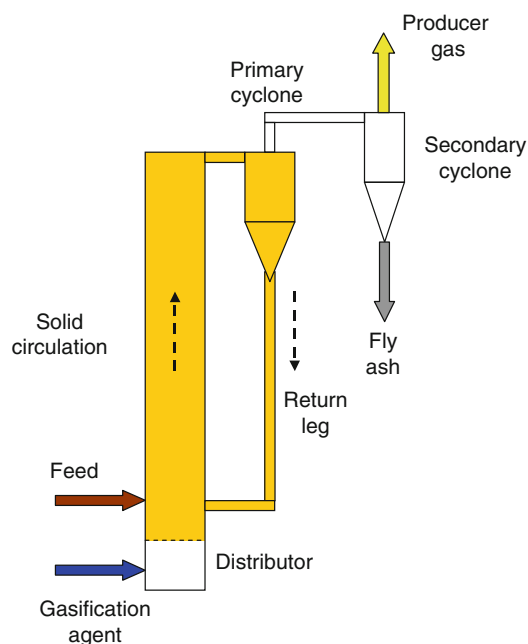
Biomass Gasification for Electricity and Fuels, Large Scale. Figure 5

Stationary (bubbling) fluidized bed gasifier

gasification agents. This gaseous mixture is blown via a plenum and distributor into the bed. But also other types of gas introduction into the fluidized bed can be found.

The solid biofuels are fed directly into the fluidized bed or thrown onto the bed to get an intensive contact with the bed material especially in the case of catalytically active materials. The producer gas leaves the gasification reactor via a freeboard where further gas-to-gas reactions take place. The gas is cooled and the fly ash is separated from the gas by a cyclone or any other type of particle precipitator. If ash also accumulates in the bubbling bed, a bed ash removal has to be foreseen. A typical cross-sectional view of a bubbling fluidized bed gasifier is shown in Fig. 5.

Fast (circulating) fluidized bed gasifiers (Fig. 6) operate at superficial velocities between 6 and 10 m/s and use smaller bed particles in the range of 0.2–0.4 mm compared to bubbling fluidized beds. There is no distinct bed height. But the total reactor is filled up with a gas/particle suspension varying in density over height. Bed material is continuously entrained at the top of the gasifier. It is returned again via a (primary) cyclone and a return leg to the reactor. Therefore, this type is also called circulating fluidized bed. Air or steam/oxygen mixtures are used as fluidization as well



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 6

Fast (circulating) fluidized bed gasifier

as gasification agent. However, the right description of the fluidization state is not circulating fluidized bed but fast fluidization.

Another type of fluidized bed gasifier for large scale is the so-called dual fluidized bed gasifier. This type has got several specific advantages especially for syngas production and is currently investigated in different forms all over the world. By combining the fluidization states (bubbling, fast) three possible configurations of dual fluidized beds are possible: two bubbling beds [14], a bubbling bed/fast fluidized bed [7], and two fast fluidized beds [18]. All these configurations are under development for producer gas generation. In Fig. 7 a dual fluidized bed gasifier with a bubbling fluidized bed and a fast fluidized bed is presented.

Dual fluidized bed gasifiers allow producing a gas free of nitrogen without the necessity of pure oxygen. One fluidized bed is dedicated for gasification (fluidized with steam) while the other one is designed for combustion (fluidized with air) in order to generate the heat for gasification. The transport of heat from the combustion to the gasification bed is carried out by circulating the bed material.

In addition to this there are also dual fluidized bed systems using alternative heat transport systems with high-temperature heat exchangers (e.g., heat pipe reformer) [11] which is currently rather dedicated to the small and medium scale.

Typical features of fluidized bed gasification can be summarized as follows:

- Temperatures: 700–900°C
- Capacities: 10–200 MW fuel power
- High fuel flexibility
 - Various kinds of fuels, fuel particles size (1–50 (100) mm), large range of ash content and water content
 - Problems with very fine particles and/or low ash melting behavior
- Medium tar content
 - Without measures: 1–20 g/Nm³ dry gas
 - With measures (catalytically active bed material): <1 g/Nm³ dry gas
- CH₄ content of about 10% (well suited for SNG production)
- Well suited for co-firing, CHP, and IGCC (integrated gasification combined cycle)

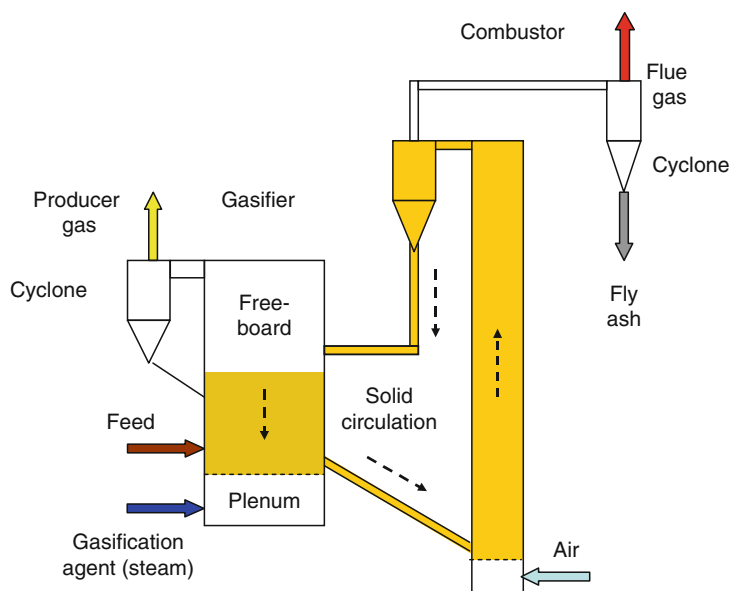
Entrained Flow Gasifiers

Within entrained flow reactors, the gasification of the biomass particles takes place within a few seconds during pneumatic transport through the reactor. This requires small biomass particle diameters and high temperatures to complete the gasification reactions within this short time. Figure. 8 shows a typical configuration of an entrained flow gasifier.

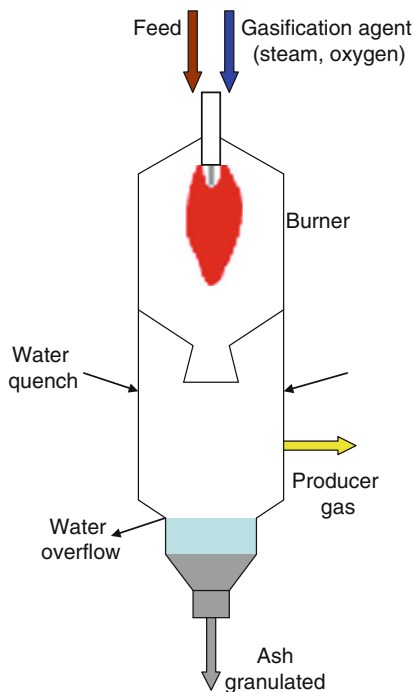
The fuel is typically fed from the top together with the gasification agent (steam/oxygen). In the upper part gasification is carried out, and in the lower part the producer gas is quenched and separated from the ash particles. The ash is withdrawn from the bottom in granulated form. Producer gas is leaving the reactor at the lower part and can be further upgraded to syngas.

The most important characteristics for entrained flow gasifiers are:

- High temperatures (>1,200°C)
- Very small fuel particle diameters are necessary (<1 mm)



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 7
Dual fluidized bed gasifier



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 8
Entrained flow gasifier after [10]

- Fuel pretreatment necessary (e.g., grinding, torrefaction, pyrolysis)
- Pressurized operation easily possible (e.g., 25 bar)
- Very low tar content within the producer gas ($<10 \text{ mg/Nm}^3$ dry gas)
- Low methane content in producer gas ($<1\%$)
- Currently for large scale application and especially for liquid biofuels production (e.g., FT-Fuels or DME from black liquor) under discussion

Producer Gas Composition

The composition of producer gas from biomass via thermal-chemical gasification is mainly dependent on the type of gasification agent and type of reactors presented above. Table 3 contains typical ranges of the syngas composition from an air-blown gasifier, a low-temperature atmospheric steam-blown dual fluidized bed gasifier, low-temperature pressurized oxygen-/steam-blown fluidized bed gasifier, and high-temperature pressurized oxygen-/steam-blown entrained flow gasifier.

The main differences are the nitrogen content, the hydrogen/carbon monoxide ratio, and the methane content. The nitrogen content is high for air-blown

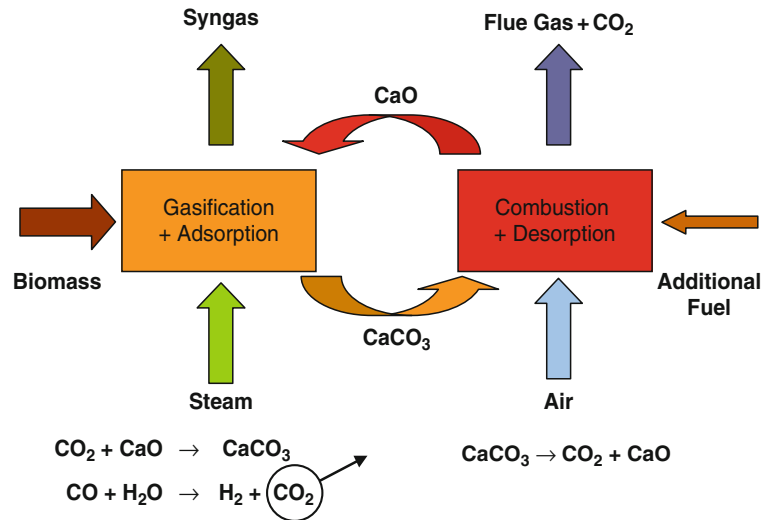
Biomass Gasification for Electricity and Fuels, Large Scale. Table 3 Typical ranges of syngas composition [8]

		Air-blown gasifier	Low-temperature atm. steam-blown fluidized bed gasifier ^a	Low-temperature press. oxygen-blown fluidized bed gasifier ^b	High-temperature press. oxygen-blown entrained flow gasifier ^c
H ₂	%	10–15	35–45	23–28	29–35
CO	%	13–17	22–25	16–19	35–44
CO ₂	%	13–16	20–23	33–38	17–22
CH ₄	%	3–6	9–11	10–13	<1
N ₂	%	42–60	<1	<5	<5

^aData from Güssing allothermal dual fluidized bed gasifier

^bData from Bioflow gasifier

^cSeveral data from CHOREN and FZ Karlsruhe



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 9

AER-gas process [22]

gasifiers. This producer gas can only be used for heat and/or electricity production. This producer gas is not beneficial for biofuels production. The hydrogen/carbon monoxide ratio is highest for the dual fluidized bed gasifier and the lowest for the entrained flow gasifier (except air-blown gasifiers). In case of methane, the lowest content can be seen for the entrained flow gasifier and much higher levels for both low-temperature fluidized bed gasifiers. This makes entrained flow gasifiers most suitable for the production of a syngas for, e.g., Fischer–Tropsch (FT) fuels and low-temperature fluidized bed gasifiers have clear advantages for SNG production.

For each of the synthesis reactions, an optimal H₂/CO ratio is necessary to obtain a maximum yield of the desired product. As most of the gasifiers are not able to produce a syngas with the desired H₂/CO ratio, this ratio has to be adjusted before entering the synthesis reactor. This is normally achieved with a water shift reaction that requires an additional step and, therefore, additional costs. In case of a dual fluidized bed reactor, this adjustment can be performed directly in the gasification reactor.

Using calcite (calcium carbonate) as bed material, the so-called AER (absorption enhanced reforming) process can be realized. The process arrangement is shown in Fig. 9. In the combustion reactor operated at

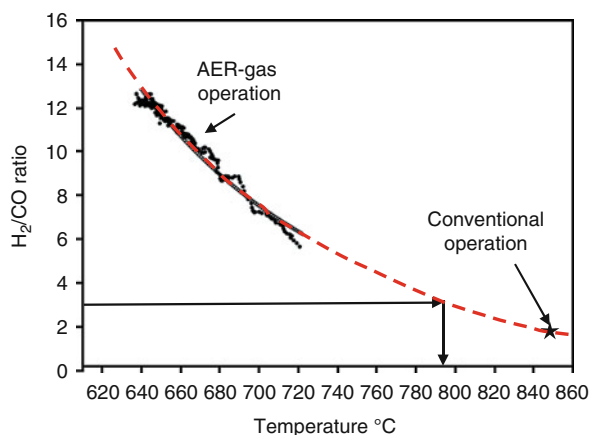
Biomass Gasification for Electricity and Fuels, Large Scale. Table 4 Comparison of conventional dual fluidized bed/AER (absorption enhanced reforming)

Component	Unit	Conventional Olivine 850°C	AER-gas Calcite 650°C
Hydrogen	Vol%	35–45	66–74
Carbon monoxide	Vol%	22–25	5–8
Carbon dioxide	Vol%	20–23	6–8
Methane	Vol%	9–11	10–12
Ethene	Vol%	2–3	1.1
H ₂ /CO	–	1.6–1.8	8–10

a temperature of about 900°C CO₂ is split off from CaCO₃ to form CaO. CaO is circulated to the gasification reactor which is operated typically at temperatures between 640°C and 720°C. In this reactor gasification takes place. Here, the CO₂ produced during the gasification process is captured by CaO to form again CaCO₃. By removing CO₂ from the gasification reactor additionally H₂ is produced by the water gas shift reaction. With this process, a hydrogen-rich gas can be produced.

A comparison of typical syngas compositions for the conventional dual fluidized bed process using olivine as bed material and a gasification temperature of 850°C and the AER process using CaCO₃ as bed material and a gasification temperature of 650°C can be seen in Table 4. As calcite is catalytically more active for tar reforming than olivine, the tar content is similar in both cases due to a lower temperature in case of calcite as bed material. In the last line of Table 4 the H₂/CO ratio is presented. According to this, the ratio is about five times higher in case of AER operation compared to conventional dual fluidized bed operation.

The AER operation leads to an extremely high H₂/CO ratio which is much higher than necessary for most of the synthesis reactions under discussion so far. By increasing the gasification temperature continuously the CO₂ capturing is reduced and, therefore, also the H₂/CO ratio (Fig. 10). This ends finally at a similar H₂/CO ratio as it is observed with olivine at a temperature of 850°C. Then the CO₂ capture is small and can be neglected.



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 10

Adjustment of the H₂/CO ratio by primary measure [22]

Options to Use the Producer Gas

Based on the statements discussed above typical syngas applications for electricity and fuel production are presented below. Electricity production via gasification can be considered as proven technology in large scale whereas for fuel production only demonstration plants are available so far. The chapter follows a very general and systematic approach as too many different plant configurations were proposed in the past. Due the fact that presenting all this different plant configurations would be too confusing, only a few successful technology routes are shown.

Power Production

Gasification offers several advantages for power production from biomass compared to combustion. These advantages are mainly:

- Possibility for utilization of applications of efficient power generation technologies dedicated for gaseous fuels also for solid biomass
- High electrical efficiencies in case of combined heat and power production
- Much easier handling of gaseous fuel compared with solid fuels

Generally, producer gas cleaning is still one crucial point in all gasification applications. Therefore, those

processes using simple and reliable process steps especially for gas cleaning are already more advanced than others.

Co-firing in Coal Power Stations The most basic option of power production via gasification concerning gas cleaning is co-firing of the producer gas in existing power stations. The motivation of this application is the reduction of CO₂ emissions due to replacement of a hard coal or lignite by biomass and/or economic advantages by using cheap waste fuels. In this case, the producer gas is normally not cooled and blown directly (i.e., without any cleaning like, e.g., tar or particle reduction) into the combustion chamber of a pulverized coal-fired power station (Fig. 11a). In such power plants circulating fluidized bed air-blown gasifiers with capacities between 50 and 100 MW fuel input are used. With such biomass or waste gasifiers up to 20% of energy of coal can be substituted by biomass or waste. Several successful plants are in operation and lots of experiences are available (e.g., Lahti plant, more than 70,000 h of operation) [10, 12].

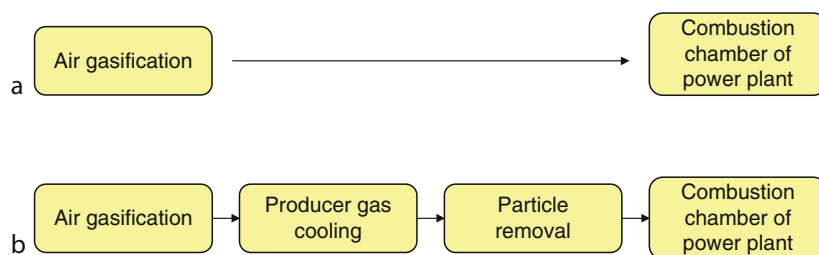
However, there are also other examples where such a very simple solution with no gas cleaning cannot be applied. If, e.g., the fly ash of the coal-fired power plant is used and has to have a certified quality, particles in the producer gas have to be removed before entering the combustion chamber of the power plant. In this case, a gas-cooling device followed by a particle separation could be integrated within the overall concept (Fig. 11b). Here problems might occur due to tar condensation and fouling in the producer gas ducts [23].

Combined Heat and Power Generation Combined heat and power (CHP) generation is applied if high overall energy utilization degrees are desired. Normally, the higher the electrical output at the same overall energy utilization degree the higher is the economic performance of such a plant. Processes using gasification allow comparable high electrical outputs and high overall energy utilization degrees at the same time which is not always the case for combustion-based systems.

For combined heat and power generation, the producer gas is fed into gas engines or gas turbines. Currently, such applications have been implemented in the small as well as in the large scale (e.g., in the capacity range of 10–25 MW fuel input). In general, such plants consist of gasification, gas cooling, gas cleaning (tar and particle separation), and utilization of the clean and cold gas in gas engines. Electrical efficiencies between 20% and 30% and overall energy utilization degrees of 75–80% can be achieved [3].

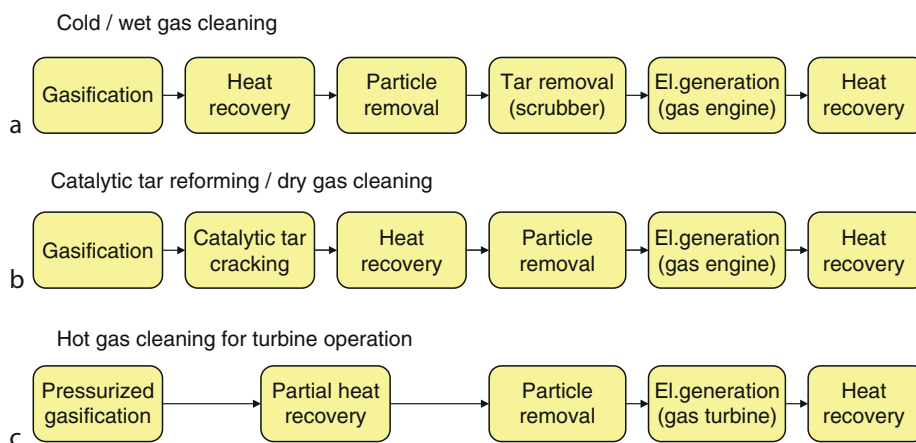
The most important process chains used currently or proposed for gas cleaning in case of heat and power production are summarized in Fig. 12. The different options are discussed below.

Currently, most installations apply cold gas or wet gas cleaning (Fig. 12a). The producer gas is generated in atmospheric air or steam gasification in fixed bed or fluidized bed gasifiers. After leaving the gasifier, the producer gas is cooled down to 180–200°C. Here the cooler construction as well as the cooler operation conditions have to be selected carefully in order to avoid tar condensation and plugging of producer gas pipes and heat exchangers. At this temperature, particles can be separated from producer gas by fabric filters



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 11

Typical arrangements for co-firing in coal power stations using biomass gasification



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 12
Typical selected process chains for combined heat and power production

or electrostatic precipitators. In some cases, pre-coated materials are used to protect the filter cloths from plugging with dust/tar mixtures. Another important parameter for a reliable operation of this cooling section is the dust to tar ratio. A certain ratio is necessary to keep the tubes and heat exchanger clean. To control this ratio, in some cases, ash is recycled and fed back into the gasifier together with the fuel.

Scrubbing of the producer gas is carried out to remove most of the tar components. This cleaning step has made enormous technical advances during the last decades. For example, water scrubbers have been replaced by different kinds of solvent scrubbers. The solvent used (e.g., biodiesel) should be cheap and able to absorb high amounts of tar per liter solvent. The saturated solvent have to be withdrawn from the scrubber and can be burnt, e.g., in the combustion part of a dual fluidized bed gasifier. Further developments aim at the regeneration of the solvent to avoid the use of high amounts of scrubber liquids [13]. In such a scrubber, additional heat can be removed to get low temperatures of the producer gas ready for feeding it into the gas engine.

In such an overall process (Fig. 12a), gas engines are used for electricity generation. Electrical efficiencies of gas engines are about 40% referred to the energy content in the producer gas. Offgas temperatures of the gas engines are about 450–500°C. This energy is normally used for operating a district heating system or for

industrial heating purposes. In gasification processes, high-temperature levels are also available as heat source as the producer gas has to be cooled down from about 850°C to 200°C and flue gas from the gas engine from 500°C to about 150°C. Therefore, nearly all processes which need heat can be satisfied.

This gas cleaning strategy (Fig. 12a) is also applied at the allothermal dual fluidized bed steam gasification realized at the Güssing plant, Austria.

Another producer gas cleaning strategy applied for combined heat and power generation is based on catalytic tar reforming [6, 21]. This strategy is also sometimes called dry gas cleaning as no scrubber is included into the process chain (Fig. 12b). Within such an overall process, the producer gas is not cooled down after gasification but led to a catalytic cracker for tar reduction. The temperature within such a device has to be above 800°C. The catalytic active compounds used within such a reactor are mostly based on metallic oxides (e.g., nickel, platinum) or nonmetallic oxides such as calcite and dolomite. This catalytic cracking can be carried out in downstream monolithic reactors or even combined in a fluidized bed gasifier using catalytic active bed material. In the latter case, the attrition of the catalysts can become a problem. So, attrition-resistant catalyst particles have to be applied [19].

After catalytic cracking of the tars, the gas can be cooled down without tar condensation problems. At

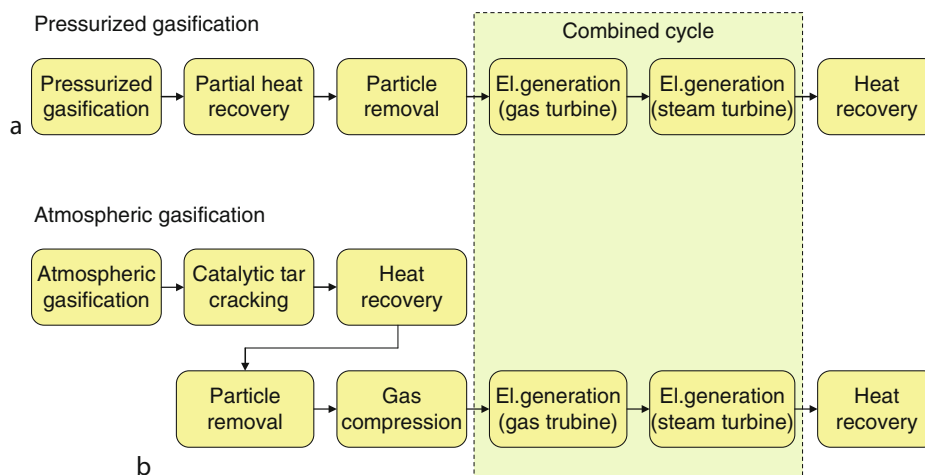
low temperatures the particles will be removed by conventional particle separation systems according to the requirements defined by the gas engines. Again, the energy in the flue gas can be utilized for district heating or other heat demanding processes (e.g., industrial applications).

Hot gas cleaning is most beneficial for pressurized gasification as it was demonstrated successfully at the Varnamo plant [10, 12]. Furthermore, this gas cleaning strategy has been developed in connection with gas turbine applications because the utilization of gas engines is limited to capacities below 10 MW_{el} (40 MW fuel input) and above this capacity, gas turbines have clear advantages. To avoid thermal energy losses, the producer gas is only partially cooled to temperatures where particle removal is economically possible (about 400–500°C). Particle separation is carried out with ceramic or metallic filter candles. Tar removal is not necessary as the producer gas is fed into a combustion chamber of the gas turbine at temperatures where no condensation takes place. Also, this fact leads to higher energy utilization as the energy content in the tar will be utilized. The heat in the flue gas at the exit of the turbine can be used for heat supply for heating applications but also for a steam process and additional power production in case of an IGCC process (see next chapter).

Power Production with IGCC Processes Highest electrical efficiencies can be obtained by using combined cycles. This means that electricity generation is carried out in two steps typically by a gas turbine process followed by a steam turbine process using the heat from the exhaust gas stream of the gas turbine. Such processes are well established for natural gas but can also be applied to producer gas from biomass gasification. Therefore, if a gasification process has to be integrated to convert solid biomass to a producer gas, the overall process is called integrated gasification combined cycle (IGCC). Due to the high complexity of an IGCC plant, this technology is only economically applicable for large scale (e.g., larger than 60 MW fuel input).

Several different process routes for biomass IGCC plants have been proposed and also demonstrated. The combination of a gas and steam turbine has been realized in two different configurations: one based on pressurized gasification and the other one on atmospheric gasification. Figure 13 shows these two different routes.

The IGCC process based on pressurized gasification (Fig. 13a) has been successfully demonstrated at Varnamo with a capacity of about 18 MW fuel input [10, 12, 6]. Air-blown circulating fluidized bed gasifiers are well suited for IGCC processes. In case of pressurized gasification, a pressure of about 20 bar is suitable. The producer gas is cooled down to about 400–500°C



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 13

Two process chains for power production using IGCC

and particles are separated at this temperature level (compare also Fig. 12c). The gas is fed into a gas turbine where about 4 MW_{el} could be obtained from the electricity generator in case of Varnamo. The exhaust gas of the gas turbine is used in a waste heat boiler to generate another 2 MW_{el} with a steam turbine coupled to an electricity generator. Waste heat can be delivered to a district heating system. The overall electrical efficiencies in future plants according to this electricity generation route can be expected in the range of 30–35%.

The IGCC process shown in Fig. 13b avoids pressurized gasification and, therefore, all the problems connected with feeding of solid fuels against a pressure of 20 bars. The gas has to be cleaned (tar, particles) and cooled down to about ambient temperature. The gas cleaning processes shown in Fig. 12a and b can be used for this purpose. This cold and clean producer gas is compressed and fed into the combustion chamber of a gas turbine. The following part can be identical to the case shown in Fig. 13a. The overall electrical efficiencies will be a little bit lower than in case of a pressurized gasification.

During the last years other combined cycles have been proposed and realized for the lower capacity range of 10–30 MW fuel input. In this case, gas engines are used as explained above. Heat available in the whole process (cooling of producer gas, exhaust gas of the gas engine) are collected with the aid of a thermo-oil and used for operation of an ORC (organic rankine cycle) process. Such plants are already realized with about 30% of overall electrical efficiencies (i.e., gas engine and ORC) [15]. Another process configuration for a combined cycle could consist of a combination of a gas engine with a conventional water/steam process.

Synthesis Applications

Gaseous and liquid biofuels have got a lot of technical advantages compared to solid biofuels. One big advantage is that they could easily be introduced into the market as the existing fossil fuel infrastructure can be used to a certain extent. Therefore, during the last decade, a lot of efforts have been made to develop and demonstrate the generation of synthetic fuel products from solid biomass. Several different synthesis processes are under consideration such as FT-synthesis (Fischer–Tropsch), methanol synthesis, mixed alcohol

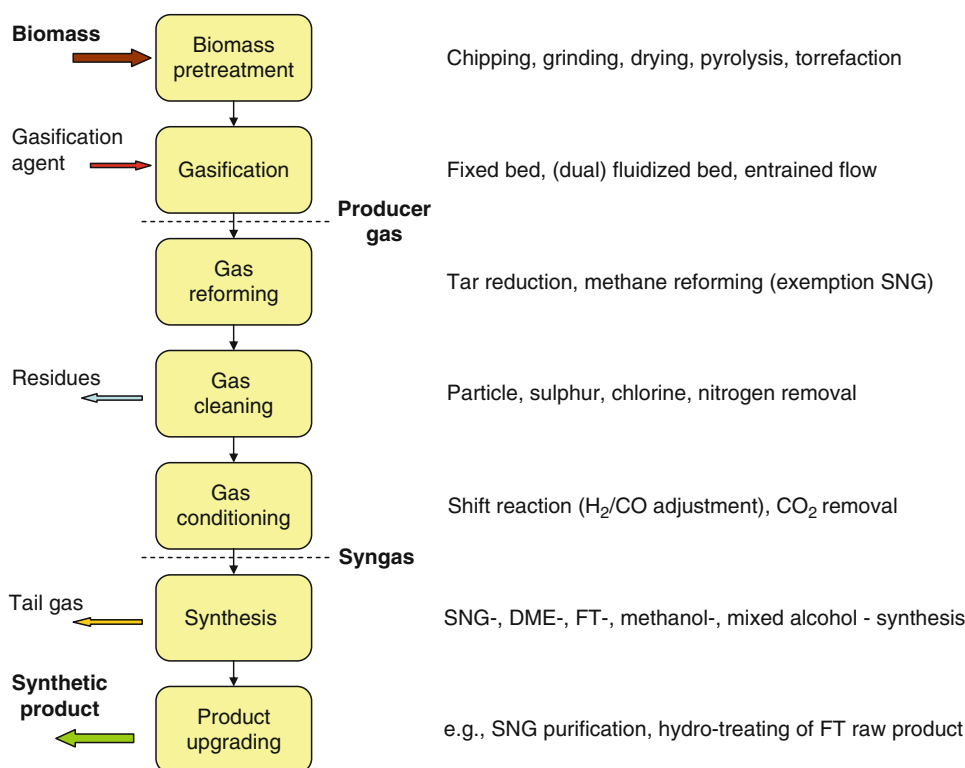
synthesis, DME synthesis (dimethylether), and production of SNG (synthetic natural gas).

Figure 14 shows an example of a typical process route from solid biomass to a synthetic biofuel. This block diagram contains the most important elements of such processes. Of course, there are processes which don't need all these steps and also others which contain even more steps. Each of the blocks can consist of several steps such as gas cleaning which summarizes particle separation as well as sulfur, nitrogen, and chlorine removal. Such possible steps are written on the right hand side of the figure. But the possibilities shown can be also alternates (e.g., fluidized bed gasifier or entrained flow gasifier). In the following, each of these process steps is discussed separately.

Biomass Pretreatment Normally, biomass has to be pretreated before feeding it into the gasifier. Chipping or grinding and drying are conventional processes to get the right particle size and the right water content for the gasifier under use. To reduce the power consumption for grinding which is necessary for an entrained flow gasifier, torrefaction has been proposed. Results show that the power consumption can be reduced by more than 80% if the biomass is torrefied. However, there is not yet too much experience with torrefaction and no large plant capacities are available.

Another pretreatment step in connection with large-scale entrained flow gasifiers is pyrolysis of the feedstock. Based on such a pyrolysis step, a mixture of pyrolysis oil and char (called slurry) can be produced. Such slurries show a higher energy density than the original biomass and, furthermore, they are quite suitable to be fed into entrained flow gasifiers. By regional distributed pyrolysis plants a large area can be made available for delivering the feedstock for a centrally located large-scale entrained flow gasifier connected, e.g., to an FT-production plant.

Gasification Reactors for Syngas Generation Gasification processes are extremely important for the production of the right producer gas for generating syngas for the respective synthesis process. The most important components in the producer gas are hydrogen (H₂) and carbon monoxide (CO). Depending on the synthesis reaction, a certain H₂ to CO ratio is necessary to get a high product yield (Table 5). From these two



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 14

Example for a typical process chain for synthetic biofuel production

Biomass Gasification for Electricity and Fuels, Large Scale. Table 5 Synthesis reactions [10, 24]

Synthesis	Beneficial H ₂ /CO ratio	Reactions
Methanol	2.05–2.15	CO + 2H ₂ = CH ₃ OH
		CO ₂ + 3H ₂ = CH ₃ OH + H ₂ O
Fischer–Tropsch	2.15	$n\text{CO} + 2n\text{H}_2 = \text{C}_n\text{H}_{2n} + n\text{H}_2\text{O}$
Mixed alcohols	1.5	$n\text{CO} + 2n\text{H}_2 = \text{C}_n\text{H}_{2n+1}\text{OH} + (n-1)\text{H}_2\text{O}$
		$n\text{CO} + (2n+1)\text{H}_2 = \text{C}_n\text{H}_{2n+2} + n\text{H}_2\text{O}$
DME	2.5 (5)	CO + 2H ₂ = CH ₃ OH
		CO ₂ + 3H ₂ = CH ₃ OH + H ₂ O
		2CH ₃ OH = CH ₃ OCH ₃ + H ₂ O
Methanation (SNG)	3	CO + 3H ₂ = CH ₄ + H ₂ O
		CO + H ₂ O = CO ₂ + H ₂

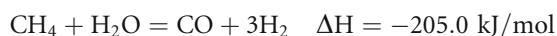
requirements gasifier using nitrogen-free gasification agents (O₂, H₂O, CO₂) seem to be the right choice. For example in “Schwarze Pumpe” fixed bed gasifiers were operated many years with oxygen/steam mixtures

as gasification agent and methanol was produced. And high-temperature gasifiers such as entrained flow gasifiers lead to a nearly methane and tar free gas (Table 3). These gasifiers are well suited for almost all synthesis

reactions except SNG production. In this case, steam-blown fluidized bed gasifiers have the advantage that part of the producer gas is already methane (9–13%) and this methane has not to be produced anymore downstream (Table 3).

The producer gas provided by the gasifier has to be cleaned and conditioned for the synthesis process.

Hydrocarbon Reforming The producer gas can obtain essential contents of methane and/or other low molecular weight hydrocarbons. This is especially the case for low-temperature (800–950°C) fluidized bed autothermal oxygen/steam gasification or allothermal steam gasification (Table 3). These components can reduce the yield of the desired synthetic product (e.g., FT-diesel) and have to be reformed before entering the gas into the synthesis reactor. Normally, steam reforming is carried out to convert the hydrocarbons into hydrogen and carbon monoxide. For methane, the reaction



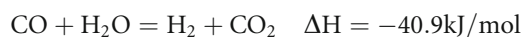
is carried out at temperatures between 800°C and 1,100°C. Typically nickel is used as a catalyst. Attention has to be drawn to catalyst poison due to sulfur compounds in producer gas. In general it is true that the higher the temperature the lower the poisoning is. Above 950°C sulfur poisoning is nearly negligible [19].

For high-temperature gasification (e.g., entrained flow gasification), the reforming step can be avoided. This is the same for low-temperature gasification and SNG production. In this case, the content of methane already existing within the producer gas is beneficial for the methanation process.

Producer Gas Cleaning Producer gas cleaning is the most crucial part in any synthetic product generation process. This is due to the extremely low concentrations of sulfur (<100 ppb) which have to be obtained to avoid poisoning of the catalysts. Sulfur is not only present within the producer gas in form of H₂S. Additionally, different kinds of organic sulfur compounds can be found in the producer gas. As the total content of sulfur has to be extremely low besides H₂S, most of the organic sulfur has to be removed as well. Methods for sulfur removal are absorption (e.g., different solvents, amines) and adsorption (e.g., ZnO, activated

carbon) processes. Similar methods have to be applied to remove nitrogen (NH₃, HCN) and chlorine compounds (HCl) also. Furthermore, particles have to be removed as well (see, e.g., [9]).

Gas Conditioning All synthetic reactions need a certain ratio of H₂/CO in order to get a maximum yield of the desired products. This ratio should be set up before feeding the syngas into the synthesis reactor. This can be carried out by using an AER-process explained above. Normally, the right ratio is obtained by using the water shift reaction described by the following reaction:



This reaction is performed between 300°C and 450°C and pressures up to 30 bars. Catalysts used for this reaction are based on iron/chromium (Fe₂O₃/CrO). In several cases, this reaction is also running in parallel in the synthesis reactor itself (e.g., SNG, Fischer–Tropsch) without the necessity of a separate step.

Another frequently proposed step for gas conditioning is the separation of CO₂ from the producer gas because producer gas coming out the gasification reactor contains CO₂ due to chemical equilibrium reasons. Further CO₂ is produced by the water gas shift reaction shown above. A too high concentration of CO₂ can be disadvantageous for some synthesis processes. A removal of CO₂ can be carried out by adsorption (e.g., pressure swing adsorption) or absorption (e.g., Rectisol, Selexol) processes.

After these conditioning steps, the producer gas is called syngas as it is now ready for the specific synthesis reactions under consideration.

Synthesis Reactions Currently, several synthesis reaction schemes are under discussion for the production of mostly liquid or gaseous biofuels for the application within the transportation sector. These reactions are summarized in Table 5 where the first three are of liquid nature and the last two led to gaseous biofuels. The reaction equations shown within this table are only the most important ones or the most desired; of course, there are also, more or less, side reactions depending on catalyst performance and reaction conditions which are not shown here.

Gas cleaning and gas conditioning are carried out to satisfy the requirements of the synthesis reactions. The reaction conditions are characterized by temperature levels of 200–400°C, pressures up to 100 bars, and the necessity of catalysts. Typical reaction conditions for these five syntheses are shown in Table 6.

The conversion during these synthesis reactions might not be complete. Therefore, a so-called tail gas containing still some small amounts of the educts will remain after the reaction and leave the synthesis process. There are two strategies to handle this tail gas [2]:

- In a fuel-oriented strategy, the nonreacted part of the tail gas will be recycled back to entrance of the synthesis reactor to maximize the production of the biofuel. This strategy is applied usually in large-scale applications.
- In a polygeneration-oriented strategy, the tail gas will be used to produce heat and power in addition to the biofuel. This strategy is proposed if heat can be used near the location of the plant.

Some of these syntheses are extremely selective such as methanol and methane syntheses. This means that practically only this hydrocarbon molecule is produced. However, this product is still mixed with other components to be separated to get the desired biofuel.

The product in case of, e.g., Fischer–Tropsch synthesis or mixed alcohol synthesis is a mixture of a certain type of molecules. In case of Fischer–Tropsch synthesis, the chain lengths of the C_nH_{2n} molecule can

vary between C_1 up to C_{70} following a probability distribution (ASF-probability function).

However, in order to get a useful biofuel for transportation which can be used in the existing fossil fuel infrastructure upgrading of the product is necessary in all cases.

Product Upgrading Upgrading of the raw synthetic products can be very different depending on the synthesis process itself and its performance. The necessary upgrading steps can be distinguished in cleaning and upgrading. Cleaning steps are mostly only separation processes of undesired components in the raw product to get the necessary final quality of the biofuel (e.g., SNG). During upgrading, the quality of the product is improved by modifying the produced synthetic molecules. Hydro-treating of the FT-raw diesel product or of the waxes is such an example.

Example for a Whole Chain of Biofuel Production

Finally, one example for the whole process chain of biofuel production is presented and explained in more detail to get a better view of the complexity of such processes. For this example SNG is selected, as a lot of experience for this process has been gathered during the last decade.

Figure 15 shows a process configuration for SNG production which has been demonstrated recently [20, 16]. The process flow diagram is built up according to the general scheme shown in Fig. 14. As pretreatment steps for the biomass fuels chipping and drying are foreseen. Gasification is carried out in an allothermal dual fluidized bed gasifier as presented in Fig. 7.

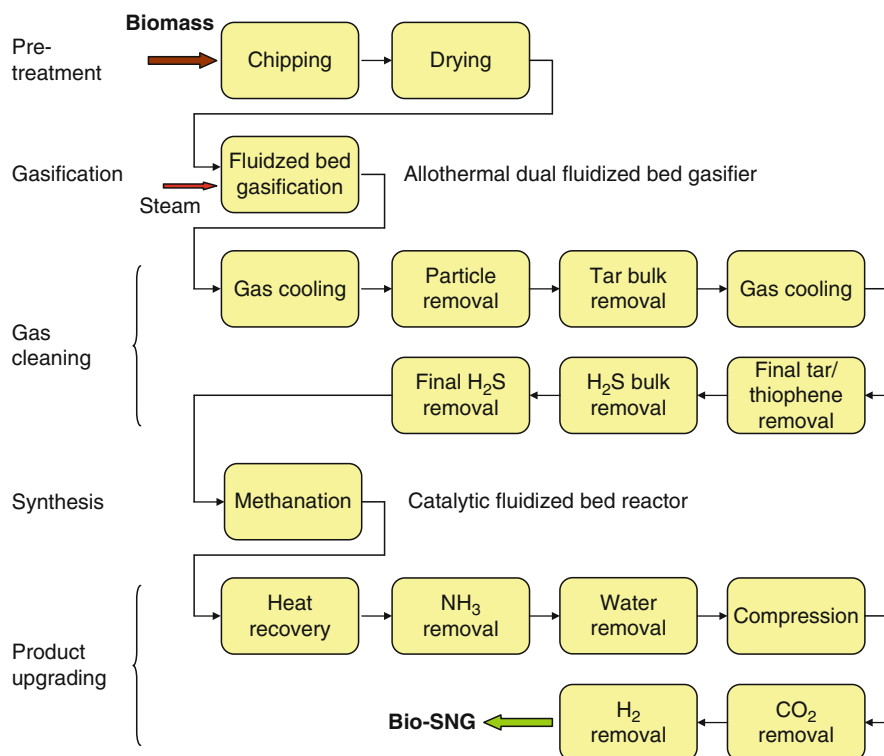
The gasification agent is steam, and gasification takes place at a temperature of about 850°C to get a hydrogen-rich gas containing nearly no nitrogen. As the temperature is low, the producer gas consists already of about 10% of methane as shown in Table 3 (column 2).

No steam reforming is foreseen in case of SNG production. Therefore, this step is left out here from the general process route in Fig. 14.

Ultra clean syngas is necessary to carry out the methanation synthesis. Therefore, gas cleaning consists of several steps before the gas can be fed into the synthesis reactor. The producer gas is cooled down to about 180°C and particles are removed

Biomass Gasification for Electricity and Fuels, Large Scale. Table 6 Ranges of suitable conditions for synthesis reactions [10], [24]

Synthesis	Catalysts	Pressure	Temperature
		Bar	°C
Methanol	Zn/Cr/Cr ₂ O ₃ /Cu	50–100	250–380
Fischer–Tropsch	Co/Fe	20–40	220–300
Mixed alcohols	MoS ₂	100	350
DME (via methanol)	Cu/ZnO/Al ₂ O ₃	5–15	250–300
Methanation (SNG)	Ni/Mg	1–10	200–400



Biomass Gasification for Electricity and Fuels, Large Scale. Figure 15

Process chain for BioSNG production [16]

using a conventional fabric filter. Calcium carbonate is applied as pre-coat material to protect the filter cloths from plugging. A scrubber serves as tar bulk removal device. As fatty acid methyl ester (FAME) is used as scrubber liquid tar is solved and high separation efficiencies are obtained. Particles from fabric filter and saturated scrubber liquid are burnt in the combustion chamber of the allothermal dual fluidized bed gasifier.

The producer gas is cooled down to about 5°C and led to a further scrubber. In this scrubber additional tar components and also thiophene, an undesired sulfur compound, is reduced down to a level which is acceptable for the methanation catalyst. Further two steps are dedicated to H₂S removal applying a H₂S scrubber and a fixed bed adsorption (ZnO) unit.

Now the producer gas has got the quality suitable to be fed into the methane synthesis reactor (syngas). The synthesis is carried out in a fluidized bed reactor with a nickel catalyst as bed material. As the reaction is

strongly exothermic, a heat exchanger is located inside the fluidized bed to keep the temperature constant at about 300°C and to obtain a high conversion rate. Alternatively, the reaction can be carried out within a fixed bed where high attention has to be led to the applied cooling strategy [17]. The exit gas of the methanation reactor consists mainly of methane, carbon dioxide, hydrogen, and steam. Methanation is an extremely selective process as nearly no further hydrocarbons are produced. Carbon monoxide is consumed more or less completely. However, this gas is not ready to be fed into a natural gas grid but has to be further upgraded.

Product upgrading in case of SNG is the second complex area besides gas cleaning explained above. Upgrading means separation of undesired gas components from the exit gas of the methanation reactor. NH₃ removal, drying, CO₂ removal and finally H₂ removal have been realized in the process mentioned above. For these steps, conventional scrubbing, adsorption, and membrane technologies are used. At the end of the

process chain, the gas is ready to be fed into the natural gas grid and has got the quality of an H-gas. This upgraded product is called Bio-SNG. The efficiency of such a SNG production can reach up to 65%.

Future Directions

This paper summarizes the state of art of biomass gasification for large-scale electricity and/or biofuels production. This state of the art can be characterized briefly as follows:

- Different gasification reactor systems are available:
 - Fixed bed (autothermal)
 - Fluidized bed (autothermal and allothermal)
 - Entrained flow (autothermal)
- Gasification agent for
 - Autothermal: air only for electricity production, steam/oxygen mixtures for electricity and/or biofuels production
 - Allothermal: steam
- H₂/CO ratio should be adjustable especially for biofuels production. Possible solutions are:
 - Downstream shift reaction
 - Dual fluidized bed (AER-process)
- Electricity production can be considered as commercially available. Main types are:
 - Co-combustion of producer gas in existing coal power stations
 - Combined heat and power production
 - IGCC processes
- Several biofuels production processes are currently under development and/or demonstration.
 - Methanol
 - Fischer–Tropsch fuels
 - Mixed alcohols
 - DME
 - Bio-SNG

Polygeneration (i.e., production of more than two products (e.g., heat, power, and biofuels)) has a great potential for biomass gasification in the future. Furthermore, developments – as far as these can be seen – are the integration and establishment of thermo-chemical platforms in bio-refineries. In nearly all bio-refineries under consideration, there are residues which can be transformed via thermal gasification in more valuable products.

However, there are still a lot of challenges to be overcome in connection with gasification and syngas production. Some important ones are:

- A secure provision and reliable pretreatment processes for biomass
- Reliable, simple, and robust gasification and gas cleaning systems
- Development of robust catalysts for synthesis processes
- Optimization of process chains and overall efficiencies

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Biomass Gasification for Rural Electrification, Small Scale

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Article Outline

Glossary

Definition of the Subject

Introduction

Generation of Electricity from Biomass via Gasification

Gasification and Gasifiers

Application of the Gas

Gas Treatment

Overall Process Chains

Future Directions

Bibliography

Glossary

Clean gas is the product gas after product gas treatment.

Gasification is the conversion of solid or liquid fuels to gaseous fuels in a reaction with an added reaction agent.

Gasifier is the reactor for the gasification.

Product gas is the burnable gas generated in the gasification, also after gas treatment. If this gas has been adapted to the specification of a downstream synthesis, it is called *synthesis gas* or *syngas*.

Product gas treatment covers all proposed processes for the modification of the product gas properties.

Product gas utilization covers all processes for the use of the product gas, mainly for the provision of other forms of energy. *Product gas application* is synonymous.

Raw gas is the product gas before product gas treatment.

Rural electrification is the mostly decentralized electrical power supply, e.g., single farms, villages, or workshops or small groups of them. The opposite is the electrification of conurbations.

Small scale is the adapted scale for the provision of a single, nonindustrial energy demand. In the case of electrical power supply, often a power range of less than about 1 MW of electrical output is called *small scale*.

Definition of the Subject

Rural electrification confronts the classical, centralized energy economy with several important challenges. The supply system is characterized by little demands scattered in the countryside. To meet each of these demands, an expensive infrastructure is necessary because of the need to connect to the national grid. That is why the costs for the installation can hardly be compensated by the distribution of electricity. Additionally, within developing countries, rural electrification based on national grids is often

not possible due to a nonexistent overall grid, and for the industrialized countries, alternatives are being searched for.

One alternative is the decentralized supply with power generator in an adapted size. Such power generators provide a good opportunity for the utilization of renewable energy. And this is especially true for biomass. Being a product of agriculture and silviculture, biomass is available in rural areas anyway and that is why the energetic use of biomass is a viable solution, e.g., for the rural electrification.

In such plants for rural electricity supply using biomass, the size of the plants is limited by several restricting factors.

- Firstly, the energy demand is relatively low because single or very few farms, villages, or workshops need to be supplied by one plant.
- Secondly, the biomass provision is easier for small-scale plants. Because biomass is available all over the countryside, large plants of several tens or hundreds of MW of fuel power are not only restricted by the total potential but also by fuel logistic. Transport distances by truck should not be longer than about 50 km in most cases for an economically viable supply. Railway or ship transport on rivers and lakes is limited to very few sites. But biomass provision of rural electrification plants also depends on other criteria. Farms and wood-processing workshops are often anxious to utilize only their own production. Being part of a self-sufficient supply chain, the biomass costs are not of such a high importance to the single user. This biomass provision also requires less organization effort.
- Thirdly, a lot of farms and workshops have a low but year-round heat demand (e.g., for drying, for heating). Because heat supply, especially if realized most time of the year, generates its own financial benefit, the installation of an energy supply plant becomes more economic if it is done in a size corresponding to the heat demand.

Because of these reasons, for rural electrification, often small-scale plants are required. Gasification-based techniques are normally able to generate electricity in the scale of kW or a few MWs more efficiently

than steam cycles. Prospectively, the gasification of biomass enables to use next-generation technology such as the fuel cell.

Apart from electricity generation, biomass gasification technique offers further interesting opportunities like synthesis of liquid and gaseous fuels or natural gas grid integration.

In general, biomass gasification is a key technology for the use of biomass especially for small-scale rural electrification.

Introduction

The basic principle of a biomass gasification plant is that the energy conversion takes place in different steps. This means that the solid biofuel is first converted into a gaseous fuel, which is more easy to utilize. This is realized based on a pure thermochemical process. Such gasification is characterized by reactions between the fuel and a gaseous reactant, the so-called gasification agent. This is also the main difference to pyrolysis which is a thermal degradation of the macromolecules biomass consists of with no additional reactant. In the case of oxygen as gasification agent, the oxygen is used in a substoichiometric amount. If oxygen is added in a stoichiometric amount, the process is called combustion. The production of substances with small molecules and which are gaseous at room temperature (like carbon monoxide, hydrogen, and methane) are the aims of the gasification.

This product, called product gas or producer gas, opens up lots of new opportunities for its application, especially after a product gas treatment. Such opportunities are, for example, the internal combustion in gas engines or gas turbines, the utilization in fuel cells, the synthesis gas chemistry, and the separation of products like hydrogen. Of special importance for rural electrification are processes which enable high efficiency electricity generation also in the small scale, especially in combined heat and power (CHP) production, like the combination of gasification and reciprocating engines.

A thermochemical gasification plant consists of biomass pretreatment, the gasification itself (also called gas generation), the product gas treatment, and the gas utilization, which in this case is electrical energy generation (Fig. 1). For the integration into the energy



Biomass Gasification for Rural Electrification, Small Scale. Figure 1

The basic process chain of a gasification plant for electricity generation

system, also the supply of the solid biofuels to the conversion plant and the distribution of the generated products (i.e., electricity, heat) is necessary, which however will not be a topic of this entry.

The main content of this entry will be the techniques for gasification, product gas treatment, and electricity generation as well as constitutive examples for overall concepts.

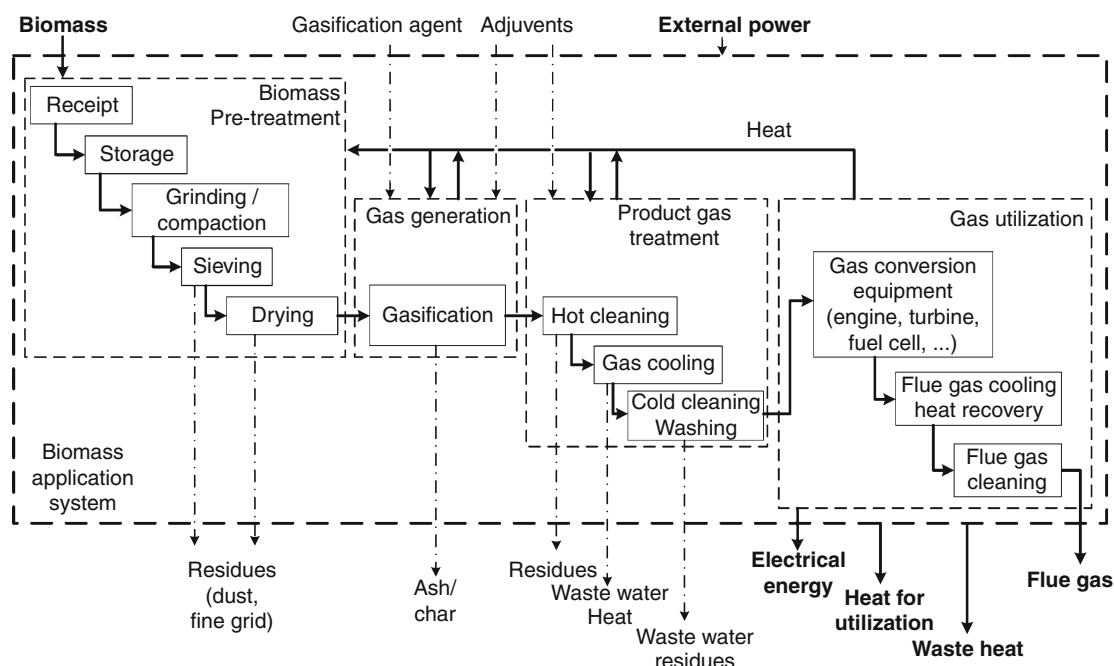
The following points are a very brief abstract of the history of biomass gasification:

Centuries BC	Production of charcoal for heating and metallurgy without gas utilization [1, S.93]
Second half of the eighteenth century AC	Start of the development of gas lightening by pyrolysis gases in England, France, the Netherlands, and Germany, involving biomass use [1, p. 244 ff]; [2, p. 241 ff];
1808	First known illuminating gas cleaning activities [2, p. 243]
First half of nineteenth century	Development of internal combustion engines for illuminating gas [1, p. 333 ff]
After 1860	Commercialization of internal combustion engines for illuminating gas by Lenoir and Otto [1, p. 344 ff]
During the nineteenth century	Use of chemicals from illuminating gas production [3] Beginning of a deliberate differentiation between gasification and (auto thermal) pyrolysis
1880	First small and mobile gasifiers by Dawson (England), decentralized gas provision for gas engines [4]

1908	First truck run on gas from wood gasification by Cazes (France) 20 hp, 10–12 km/h, in the following development activities mainly in France [4]
1921	Imbert constructs his first biomass gasifier, start of extensive activities in the following decades [3]
1930s and 1940s	Wood gas for motor vehicles (cars, trucks, etc.) in countries which are cut off from crude oil supply, a several hundred thousands of gasifiers are built in Germany [3–5]
1950s	Nearly all of these systems are replaced by the utilization of gasoline and diesel
From the late 1970s	First restart of biomass gasification activities after the first oil crisis, new focus: power generation, especially in decentralized and small systems (e.g., [6–8])
1990s	Start of the development of a lot of gasification systems driven by the idea of renewable energy supply (e.g., [9–12])
	Start of the research and development work on systems which are currently constitutive, like the Güssing FICFB gasifier [13]
Since about 2000	Start of the commercialization, increased activities in the field of synthetic fuel production

Generation of Electricity from Biomass via Gasification

In comparison with energy conversion chains for the electricity production applying solid fuels like the combustion steam cycle processes, the basic principle of a gasification plant is that energy conversion is realized in different steps. For this reason, a thermochemical gasification plant consists of biomass pretreatment, gasification (also called gas generation), product gas treatment, and gas utilization (here electricity generation). A general survey is shown in Fig. 2. For the



Biomass Gasification for Rural Electrification, Small Scale. Figure 2
General outline of a biomass gasification plant

integration into the energy system also, biomass supply and distribution of the generated products are necessary.

The biomass pretreatment serves for adapting the quality of the biomass delivered to the conversion plant to the requirements of the plant, which are mainly defined by the gasifier. Typical steps of the biomass pretreatment are receipt, storage, grinding, or compaction for the adaptation of the particle size, sieving to ensure that the desired range of fuel size is fulfilled and drying for the adjustment of the required water content. Many different solutions and designs are available for each of these steps. They are similar to the pretreatment for other chains using biomass (e.g., combustion, pyrolysis).

The heart of the conversion plant is the gas generation. In this part, the solid biofuel is converted into a gaseous fuel. The process is straight thermochemical. Thus, the gasification of solid biomass is characterized by reactions between the fuel and a gaseous reactant (i.e., gasification agent). The goal is to produce substances with small molecules gaseous at room temperature (like carbon monoxide, hydrogen, methane).

Because the quality of the provided product gas in most cases is not good enough for the proposed gas utilization, different steps of product gas treatment are necessary (i.e., gas cooling, gas cleaning). The gas cleaning can be realized either before the gas cooling at high temperatures or after gas cooling at low temperatures. In any case, the required product gas treatment is determined by the gap between the gas quality provided by the gasifier and the requirements of the gas utilization.

This product gas opens up lots of opportunities for its application. Such opportunities are, for example, the internal combustion in gas engines or gas turbines and the utilization in fuel cells. Additionally such electricity generation can be combined with a heat provision (i.e., CHP). For the heat supply, different heat flows from product gas treatment and from gas utilization can be used. Due to environmental reasons, often additionally a flue gas cleaning is necessary.

Gasification and Gasifiers

The heart of a gasification plant for electricity supply is the gasification, occurring in a gasifier. This entry deals

with the process of gasification and its partial process and the gasifiers as reactors the gasification occurs in.

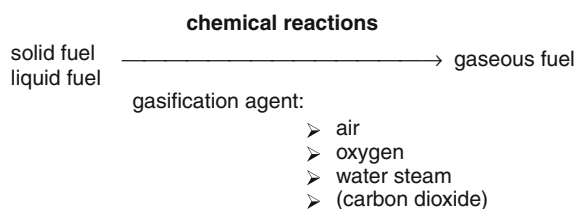
Chemical Basics

Biomass gasification is a thermochemical process. The overall process is characterized by the following process steps.

1. Drying
2. Pyrolytic decomposition
3. Oxidation
4. Reduction
5. Gas phase reactions

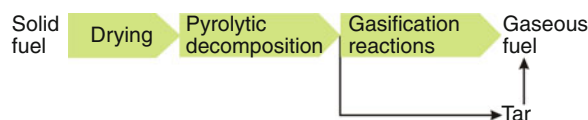
The importance of the different steps varies depending on the technical frame conditions and their order may change from process to process. Being the reactions employing the gasification the gasification agent, the oxidation, the reduction, and the gas phase reactions can be subsumed as gasification reactions. Regarding this, the gasification can be described as shown in Fig. 3.

The reactions of the gasification process can be summarized as follows.



The process steps can be described as follows mainly (see [11, 12]).

Drying The drying is the removal of physically bonded water by vaporization. This is an endothermic process. Drying did not change the chemical properties of the biomass.

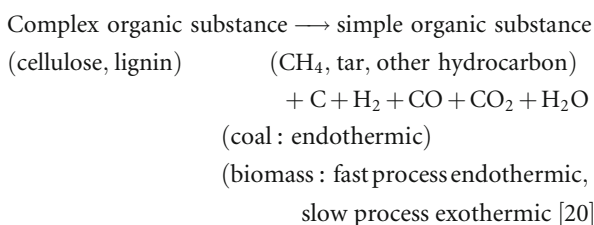


Biomass Gasification for Rural Electrification, Small Scale. Figure 3

Basic steps of gasification

Pyrolytic Decomposition (Degassing, Carbonization)

The aim of the pyrolytic decomposition is destroying of organic macromolecules by providing fixed carbon and volatile organic substances (see [14–19]). Products are pyrolysis coke (especially charcoal), pyrolysis gas, and tar. The relative amount of each fraction and its composition strongly depends on the parameters chosen for the pyrolysis process (i.e., reactor type, heating rate, residence time, pressure, and maximum temperature). This is summarized below [20].



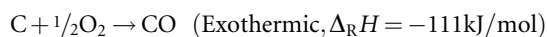
Pyrolytic decomposition starts with several structural changes within the lignocellulosic biomass. The main reactions at lower temperatures are depolymerization as well as dehydration, decarbonylation, and decarboxylation. As a consequence, water, carbon monoxide, and carbon dioxide are released from the solid biofuel. The hemicelluloses undergo thermal decomposition readily between 200°C and 300°C, while thermal degradation of cellulose dominates at 325–375°C. Lignin decomposition occurs mainly at temperatures above 375°C. However, due to its complex structure, lignin degradation covers a larger temperature interval. In general, at higher temperatures, the solid or liquid product of this pyrolytic decomposition becomes more aromatic.

When the gaseous and vaporous products of pyrolytic decomposition remain in areas with high temperatures, the initially formed tars and other hydrocarbons may be converted into other compounds due to thermochemical processes taking place within the gas phase (e.g., cracking). Otherwise, these substances will stay in the product gas.

Gasification Reactions The gasification reactions (e.g., [21–24]) are these chemical reactions which involve the gasification agent. Such reactions are oxidation and reduction reactions utilizing the fixed carbon as well as homogenous reactions in the gas phase

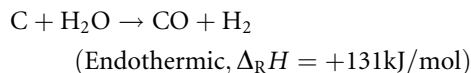
utilizing gaseous reactants. During these gasification processes, pyrolysis residues react with a gasification agent (e.g., water, carbon dioxide, deficit oxygen/air) to generate a gaseous secondary energy source. Ideally, only carbon monoxide and hydrogen are formed. But due to the chemical equilibrium also, other components such as carbon dioxide, water, methane, and higher hydrocarbons are produced and, thus, ingredients of the gas generated by the gasifier. The carbon monoxide/hydrogen ratio is determined by the choice of gasification agent.

Below the most important reactions are presented:
Oxidation

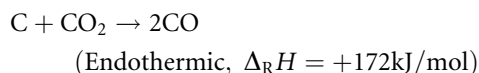


The main goal of the oxidation step is it to provide the reaction energy for the endothermic reactions. If an oxygen-free gasification agent is used, these oxidation reactions will not take place due to a lack of oxygen. That is why in these cases an external heat input is necessary.

Reduction



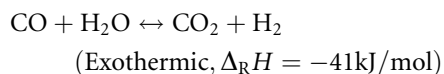
“heterogeneous water gas reaction”



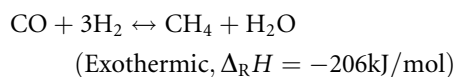
“Boudouard reaction”

Based on these reduction reactions, carbon monoxide and hydrogen are generated. These are mainly the target products of the gasification.

Homogenous reactions (gas phase)



“water gas shift-reaction”



“methanation”

Within the gas phase, different secondary reactions of the hydrocarbons, especially of tars, take place.

Depending on the reaction conditions, the most important processes are:

- Cracking
- Steam reforming
- Partial oxidation
- Hydrogenation

All reactions involved within gasification are equilibrium reactions. Hence, the temperature has a major influence on the final product composition. As especially oxidation reactions and the methanation are exothermic, these reactions dominate at lower temperatures. In contrast, formation of carbon monoxide and hydrogen from carbon and water according to the heterogeneous water gas reaction as well as the Boudouard reaction is endothermic, and thus these transformations are facilitated by higher temperatures.

Normally, the generated products should continue to react until chemical equilibrium is reached. At typical gasification temperatures, this equilibrium is characterized by a tar-free gas [25]. But such an equilibrium stage is not reached in any single-stage gasifiers. And then equilibration comes to an end (freezes) with decreasing temperatures as it is the case after the producer gas has left the gasifier. That is why often the gas composition generated in biomass gasifiers differs significantly from the equilibrium composition [26]. Because of that, the tar containing gases had to stay within the high-temperature area, preferably more than 1,000°C for several seconds, for complete destruction of tar.

Technical Basics

Being a reaction between fuel and gasification agent, the gasification is mainly determined by the gasification agent. Major gasification agents are:

- Air
- Oxygen
- Water-steam
- Carbon dioxide

Carbon dioxide, however, is hardly used as pure gas but sometimes in flue gas recirculation. Oxygen is unusual in small-scale plants, because there are no adequate small-scale oxygen provision systems. The same is basically true for water-steam. This is

the reason why small-scale gasification systems are usually operated with air.

Important process steps of gasification (like the reduction step), forming the desired products carbon monoxide and hydrogen, are endothermic. This requires a heat supply. Two ways are possible:

- *The allothermic process with heat supply from external sources.* The heat is transferred into the gasifier by recuperation or by hot material flows. Typically, water-steam is used as gasification agent in allothermic processes.
- *The autothermic process.* In this process, the required heat is produced by combustion of a part of the fuel. Therefore, the gasification agent has to contain portions of air or oxygen because the main exothermal (heat delivering) reactions are the oxidation reactions.

In general, the allothermic process is technologically more demanding. For this reason, in the small scale, mostly autothermic processes are realized. Allothermic systems are built mostly with larger thermal capacities.

Reactor Principles

For biomass gasification, lots of different reactors (e.g., [9, 27–31]), in this case called gasifiers, have been developed. An overview is shown in Fig. 4.

These reactors are based on a few principles of gas-solid reactors. Most of the common reactor principles have been considered for the design of gasifiers, both

separately and in combination. Therefore, the following cases are discussed:

- Single-stage gasifiers
- Multistage gasifiers

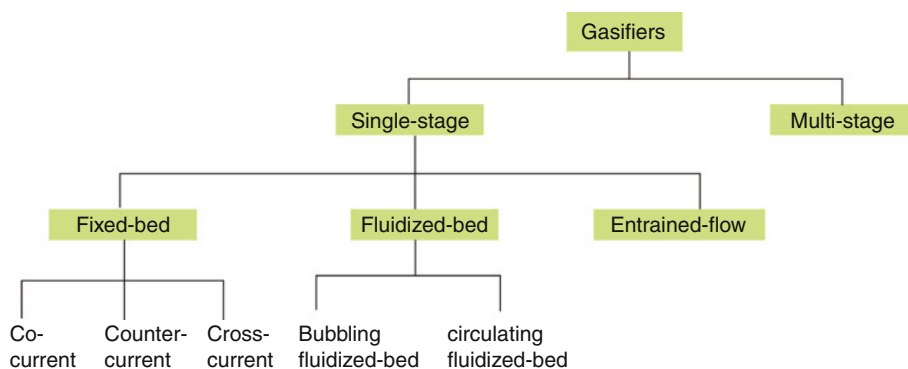
Single-stage gasifiers represent different reactor principles, in particular:

- Fixed-bed gasifiers
- Fluidized-bed gasifiers
- Entrained-flow gasifiers

Multistage gasifiers are characterized by a functional combination of reactor principles for purposeful separation of reactions.

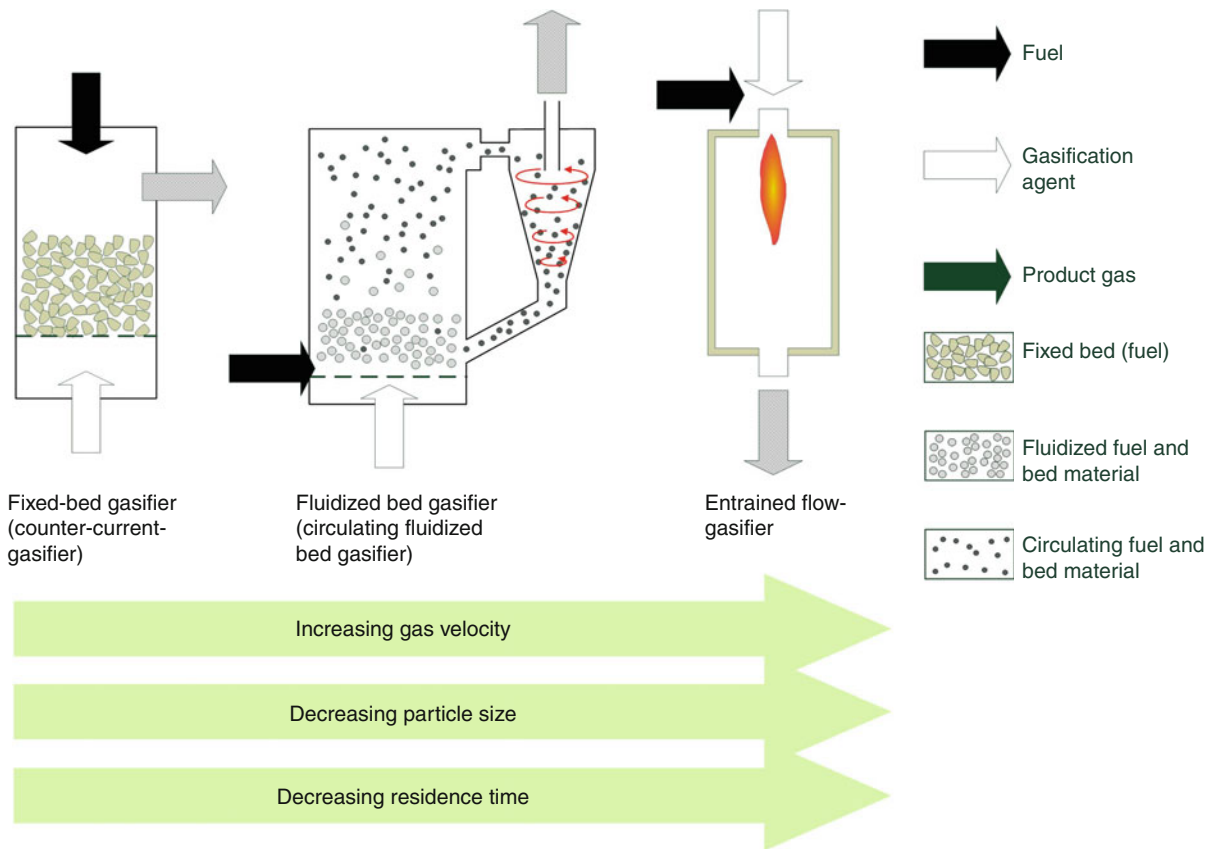
The basic design of a fixed-bed gasifier, a fluidized-bed gasifier, and an entrained-flow gasifier is shown in Fig. 5. Gas velocity, particle size, and residence time are characteristic parameters for these reactor types. The relation of these parameters is also shown in this figure.

Fixed-Bed Gasifiers The main feature of fixed-bed reactors (e.g., [11, 12, 29]) is that the solid phase is placed on a supporting structure, such as grates or fire-proof plates. The force from the fluid phase to the solid phase (resisting force) is low compared with the force of gravity. Even if the resisting force is directed against the gravity force, the solid phase cannot be moved by the resisting force but only by external forces. Being exposed to little movement, the solid phase will mix to a low extent and separated zones can develop, each dominated by a special process step.



Biomass Gasification for Rural Electrification, Small Scale. Figure 4

Overview of reactor types of gasifiers



Biomass Gasification for Rural Electrification, Small Scale. Figure 5

The basic reactor types of single-stage gasifiers

There are three types of fixed-bed gasifiers which differ by the direction of movement of the solid fuel and the gases.

Countercurrent gasifier In a countercurrent gasifier (e.g., [7, 8, 32, 33]), the solid fuel and the gases (gasification agent and product gas) move in opposite directions. Normally the solid fuel moves in the direction of the gravity force and the gases rise.

The basic design of a countercurrent gasifier is shown in Fig. 6. Typical is the following order of the process steps from the bottom (grate) to the top of the reactor:

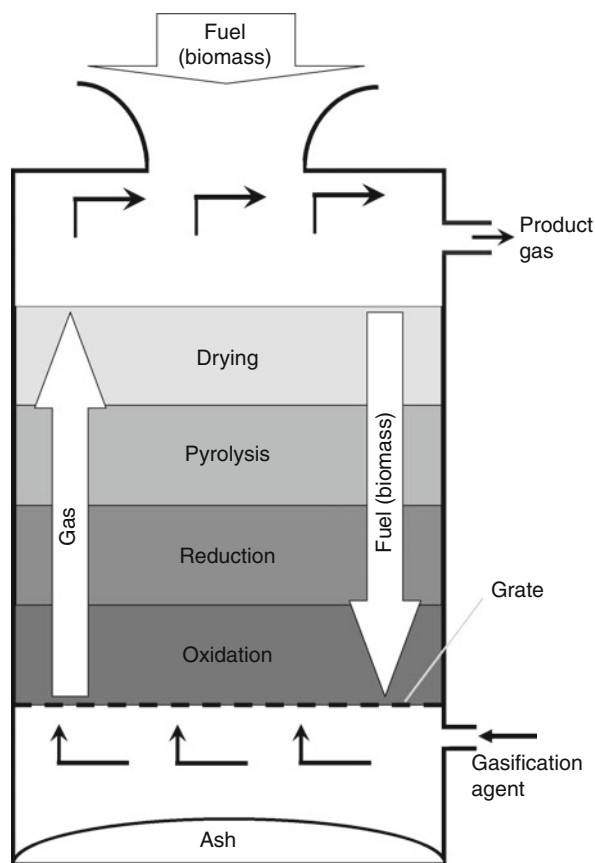
1. Oxidation
2. Reduction
3. Pyrolysis
4. Drying

This means that the hydrocarbons formed during the pyrolytic decomposition, especially the tar, do not

flow through a high-temperature area. They only pass through the drying zone. That is why the tar content in the raw product gas is significantly high.

But this principle also has advantages:

- Because of the order of the process steps, the fuel is dried by the heat of the product gas. That is why wet fuels can be used. This is also the reason of its high overall gasification efficiency.
- Fuel with a wide range of particle sizes is less problematic because of a self-regulation of the flow direction.
- As the gasification agent can easily be spread evenly by the grate, the countercurrent gasifier is the fixed-bed gasifier which can most easily be scaled up.
- Because the solid matter is at last in contact with the inserted gasification agent, it is possible to reach a carbon-depleted ash. With the gasification agent air (or oxygen), the ash can become nearly carbon free.

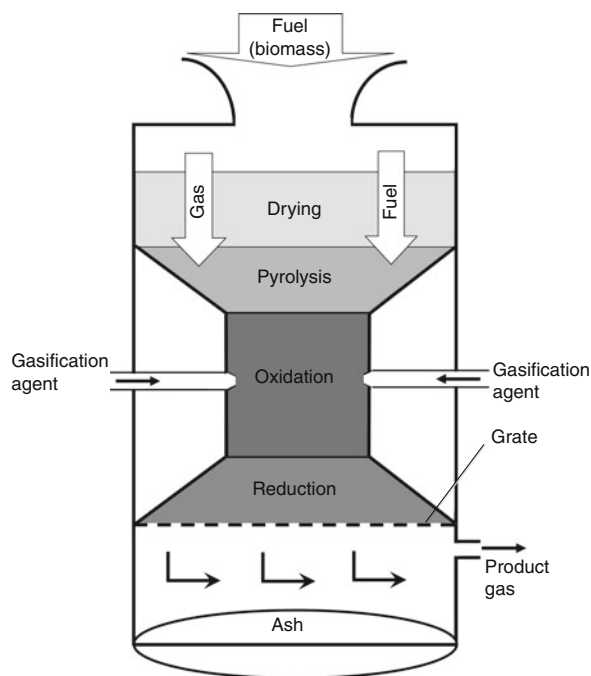


Biomass Gasification for Rural Electrification, Small Scale. Figure 6
Countercurrent gasifier

Basic technical properties of countercurrent gasifiers (reference values) are shown in [Tables 1–3](#).

Cocurrent gasifier In a cocurrent gasifier (e.g., [34, 35]), the solid fuel and the gases move through the whole gasifier, mainly in the same direction. Normally, solid fuel moves in the direction of the gravity force and so do the gases.

The basic design of a cocurrent gasifier is shown in [Fig. 7](#). The gasification agent may be fed from the top of the fuel bed using the whole cross section (open-top gasifier). However, the feed-in of the gasification agent into the oxidation zone through nozzles is more common. Typical is the following order of the process steps from the bottom to the top of the reactor:



Biomass Gasification for Rural Electrification, Small Scale. Figure 7
Cocurrent gasifier

1. Reduction
2. Oxidation
3. Pyrolysis
4. Drying

This means that the gases from the pyrolytic decomposition, especially the tar, pass the oxidation and reduction zones while flowing downward. Thereby, the tar is supposed to be cracked by the high temperatures and the tar content in the raw product gas should be very low.

But the flow conditions in commercial scale cocurrent gasifiers, especially in gasifiers with nozzles, are normally not found to be ideal [35]. That is why usually areas with temperatures exist which are too low for cracking of tars. In those parts of the flow, which pass these areas, little or no tar is cracked. That is why a nearly tar-free gas cannot be achieved in a commercial scale cocurrent gasifier.

Although the tar content in the raw product gas is much lower than in a countercurrent gasifier,

Biomass Gasification for Rural Electrification, Small Scale. Table 1 Typical power range, fuel requirements, and efficiencies for the basic principles of gasifiers [38]

	Fixed bed		Fluidized bed
	Countercurrent	Cocurrent	
Common power range [MW] ^a	0.1–10	0.02–3	8–100
Fuel requirements			
Grain characteristic	Coarse-grained	Coarse-grained, narrow range of grain size	Fine-grained, narrow range of grain size
Grain size [mm]	5–100	20–100	10–100
Water content [mass-%]	12–40 (60)	12–25	< 40
Ash content [mass-% _{wf}]	< 15	< 5	k. A.
Cold gas efficiency [%]	50–70	65–75	65–85

^aFuel input

Biomass Gasification for Rural Electrification, Small Scale. Table 2 Typical gas composition for the basic principles of gasifiers with air as the gasification agent [11, 32, 39]

	Fixed bed		Fluidized bed	
	Cocurrent	Countercurrent	Bubbling	Circulating
Reference water content [% dm]	≈ 6	≈ 50	≈ 15	≈ 15
H ₂ [volume-%]	15–21	10–15	≈ 10	15–22
CO [volume-%]	10–22	15–20	≈ 15	13–15
CO ₂ [volume-%]	11–13	8–10	≈ 17	13–15
CH ₄ [volume-%]	1–5	2–3	≈ 4	2–4
C _n H _m [volume-%]	0.5–2		≈ 1.6	≈ 2
N ₂ [volume-%]	Rest	Rest	Rest	Rest
Lower heating value [MJ/Nm ³]	4.0–5.6	3.7–5.1	≈ 4.5	3.6–5.9

the cocurrent principle has still the following disadvantages:

- Leaving the gasifier directly after the reduction zone at high temperature, the heat of the product gas cannot be used in the gasifier (e.g., for drying of the fuel). That is why only relatively dry fuel can be gasified and the gasification efficiency is relatively low.
- The particle sizes have to be within a narrow range.
- The gasification agent is fed into the gasifier through nozzles. This makes it very challenging to spread the gasification agent evenly through the gasifier; because of physical constraints, the gasification agent penetrates only a few centimeters into the fuel bed crosswise to the main flow [35]. That is why a scale-up of cocurrent gasifiers to sizes higher than in test facilities is extremely complicated. For this reason the tar content in the raw product gas rises with increasing gasifier sizes.
- Because the solid matter is at last in contact with the product gas, due to reasons related to the chemical equilibrium, it is not possible to reach

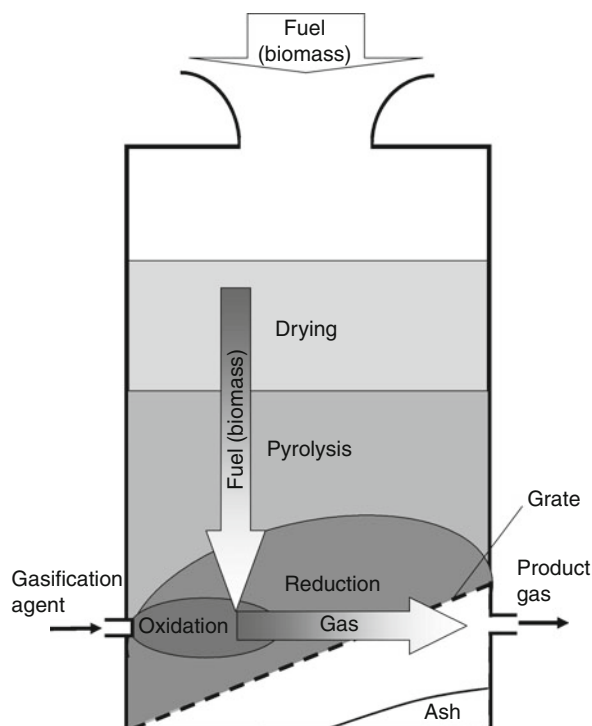
Biomass Gasification for Rural Electrification, Small Scale. Table 3 Comparison of the basic principles of gasifiers [29, 31]

Fixed-bed gasifiers	Fluidized-bed gasifier	Entrained-flow gasifier
<ul style="list-style-type: none"> + Suitable for small and very small plants + Unpretentious technique 	<ul style="list-style-type: none"> + Very good heat and mass transfer + High space and time yield + Low product gas temperature (high chemical efficiency, uncomplex gas cooling) 	<ul style="list-style-type: none"> + High carbon conversion rate + High reaction velocity + Low start-up and rack out time
<ul style="list-style-type: none"> o Reaction zones existing o A lot of different concepts 	<ul style="list-style-type: none"> o No reaction zones 	<ul style="list-style-type: none"> o Low methane content in product gas
<ul style="list-style-type: none"> – Slow regulation action – Very long start-up time – Difficult automation 	<ul style="list-style-type: none"> – Limited carbon conversion rate – Carbon-containing ash – Linkage between particle size and fluidization velocity 	<ul style="list-style-type: none"> – Only very small fuel particles possible – Very expensive biomass pretreatment – High product gas temperature (low chemical efficiency, complex gas cooling) – Only very large plants reasonable

a carbon-depleted ash. Thus, the refuse of a single-stage cocurrent gasifier contains several percents of carbon. This lowers the overall efficiency. And, for example, in Germany, the disposal of this ash-carbon-mixture is problematic because the carbon content of material to be dumped on a landfill is limited by law.

Basic technical properties of countercurrent gasifiers (reference values) are shown in Tables 1–3.

Cocurrent gasifiers have been used in the years around World War II in transport applications,



Biomass Gasification for Rural Electrification, Small Scale. Figure 8
Crosscurrent gasifier

especially in trucks. This is one reason for the many newly developed systems based on the principle of cocurrent gasification.

But the success under those days' conditions is not sufficient for a successful use in energy applications today. For example, running times of only a few hundred hours and a lot of maintenance work are normally not tolerable nowadays. One of the main requirements for an energy system today is the high availability. This has to be fulfilled also by the gasification processes.

Crosscurrent gasifier In a crosscurrent gasifier (e.g., [9, 36, 37]), the solid fuel and the gases (gasification agent and product gas) move crosswise to each other. Normally, the solid fuel moves in the direction of gravity force. The gasification agent is horizontally injected through a nozzle. And the product gas is also discharged horizontally.

The basic design of a crosscurrent gasifier is shown in Fig. 8. The order of the areas for the process steps in

formed depending on the distance to the nozzle and the shortest way from gas inlet (nozzle) to gas outlet (see Fig. 8).

Because of this special design, the residence time of gases in the gasifier is short. That is why the gas composition can differ from the equilibrium composition, especially the carbon monoxide content can be lower. Only in those parts of the gas, which pass through a high-temperature area, the tars can be cracked. Therefore, the tar content in the raw product gas is higher than in the product gas from cocurrent gasifier.

The crosscurrent gasifier is ready for operation in a short time and enables response to fast variations of load. The gasifier can be built relatively compact.

This type of gasifier has been used in the first half of the twentieth century for transportation purpose. In recent years, there have been some activities for using that gasifier type for renewable energy production in Germany. But, currently, this development is of minor importance.

Fluidized-Bed Gasifiers The main characteristic of fluidized-bed gasifiers (e.g., [11, 12, 29]) is the force equilibrium between the resisting force (the force from the fluid phase to the solid phase) and the force of gravity. Therefore, in a fluidized-bed reactor, the fluid phase has to flow against the force of gravity, that is, vertically upward. This equilibrium of forces depends on the mass of solid particles and the flow velocity of the fluid phase. Particle size is important for unproblematic running of a fluidized-bed reactor. The solid particles float in the fluid flow. Due to the equilibrium of forces, the particles remain in a layer. Particles being too heavy move downward, particles being too light, for example, after a weight-loss during reaction, are blown out of the layer.

The particles in the layer are very well mixed. Causative for the mixing are inhomogeneities in the flow, that is, slight changes in fluid speed and flow direction. Thus, the equilibrium of forces is temporarily disturbed. A resulting force is the outcome. This force changes the direction of the particles. Hence, the particles move chaotically. Another reason is that like in all streamer tubes, also in the fluidized-bed reactor, the velocity near to the wall is lower than in the middle. Because of the force equilibrium, near to the wall, particles go down and in the middle

come up. Thus, a circulation is also realized within the particle bed.

In fluidized-bed reactors for combustion and gasification, normally an inert (not reacting) material is used for heat storage and temperature leveling. The leveled temperatures and the stored heat are great advantages of fluidized-bed reactors, because changes in the fuel quality will partly be compensated.

Because of the mixing of the solid phase, no separated zones will develop. All process steps occur simultaneously and close to each other, that is, there are more or less, the same chemical behaviors all over the fluidized bed. Because all gasification reactions are equilibrium reactions, and for this reason, the chemical reaction occurs only up to the equilibrium, the carbon cannot be converted totally. That is why carbon remains in the ash from single-stage fluidized-bed reactors.

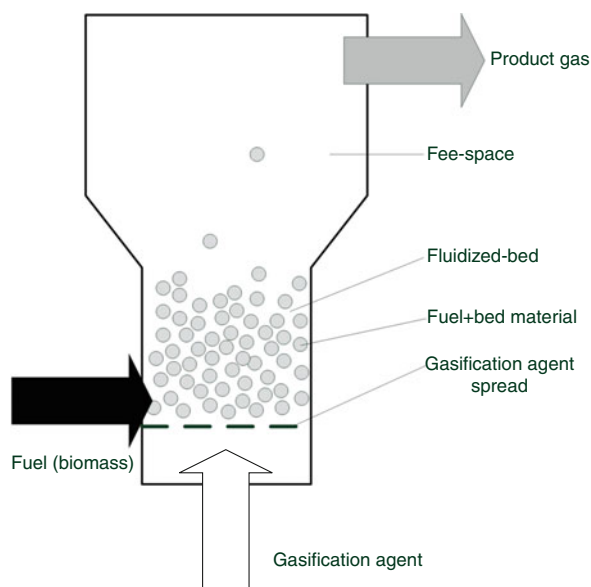
There are two main types of fluidized-bed gasifiers outlined below:

- The bubbling-fluidized-bed gasifier (BFB)
- The circulating-fluidized-bed gasifier (CFB)

Basic technical properties of fluidized-bed gasifiers (reference values) are shown in Tables 1–3.

Bubbling-fluidized-bed gasifier (BFB) In a bubbling-fluidized-bed gasifier, nearly all reactions including the solid fuel as reaction partner take place in the fluidized bed. Particles blown out because of too low weight mainly consist of ash because the gas–solid reactions are almost finished when weight of a particle becomes so low. These particles will be separated and disposed of. A recirculation of particles into the reactor is usually not realized. The basic design of a bubbling-fluidized-bed gasifier is shown in Fig. 9.

Circulating-fluidized-bed gasifier (CFB) In a circulating-fluidized-bed gasifier, only a portion of the solid fuel reacts in the fluidized bed. Lighter particles are blown out even if the reactions are not completed and organic matter remains. The target is that a main part not only of the gas phase reactions but also of the gas–solid reactions occurs in the space above the fluidized bed, the so-called free space. At the end of the free space, the remaining particles are separated from the gas. Usually a cyclone is used but also other mechanical gas–solid-separators are possible and tested in different designs. Containing a lot of remaining organic matter which is possible to gasify



Biomass Gasification for Rural Electrification, Small Scale. Figure 9
Bubbling-fluidized-bed gasifier

a major portion of the separated particles is recirculated into the reactor. The basic design of a Circulating-fluidized-bed gasifier is shown in Fig. 10.

Entrained-Flow Reactor In an entrained-flow reactor (e.g., [30, 31]), the force from the fluid phase to the solid phase (resisting force) is much higher than the force of gravity. The particles are carried along with the fluid phase. The reactions take place while the particles are transported by the fluid phase.

In order to facilitate the transport of fuel particles by the gases, very small fuel particles with a size of less than 1 mm are utilized in entrained-flow gasifiers. Thus the residence time is very short (normally a few seconds or less) and the reaction temperatures are high.

Coal gasifiers in a scale of several hundred MW are often built as entrained-flow reactors. This scale is uncommon for the utilization of biomass. The chopping of biomass to the necessary particle size is expensive and normally only possible with a thermal pretreatment.

A comparison between entrained-flow gasifiers and the other basic principles is presented in Table 3.

Multistage Gasifiers Because of different conditions required by each reaction, it is not possible to

optimize all gasification reactions in a single-stage gasifier. Especially the temperature window and residence time for a certain reaction step is often not optimal or appropriate, for example, for tar removal. One idea to solve this problem is to use different reactors for different process steps and reactions. These different reactors can be optimized more easily for reactions taking place in them. On the other hand, the costs may increase by using more than one reactor.

Various combinations have been designed using different types of reactors and dividing the gasification into different sub-processes. Below only a few selected examples are described briefly.

Double fire gasifier This gasifier principle (e.g., [9, 27, 40–42]) got its name, because it is a combination of a cocurrent and a countercurrent gasifier in one shell. Transported by the gravity force, the fuel first passes the cocurrent and then the countercurrent part. The biomass is fed into the cocurrent part. In the zone of the pyrolytic decomposition, volatile substances are released. Like in a single-step cocurrent gasifier, the tar is cracked in the hot zones of this part. For the cocurrent part, there is a first gasification agent inlet with nozzles.

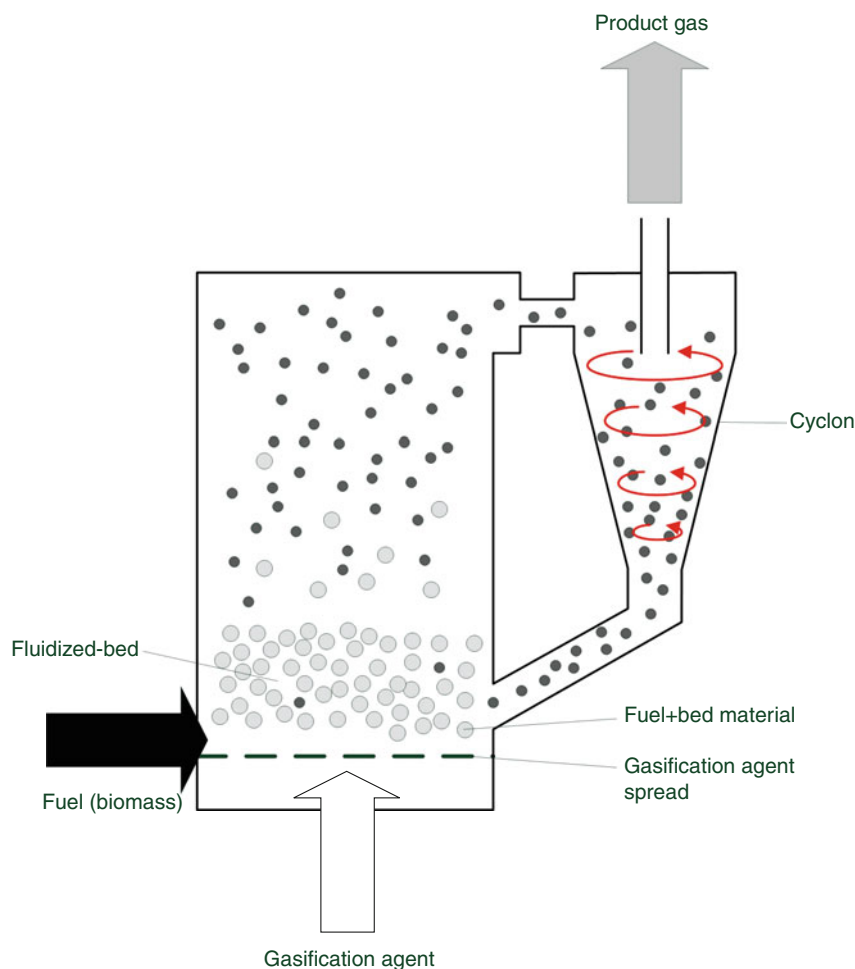
Only the carbon-rich residue from the cocurrent part moves to the countercurrent part. Because of the gasification agent inlet from the bottom (grate), the carbon remaining after the cocurrent stage is utilized in the countercurrent stage. Between the stages, there is no separating device like a grate. Only the position of the product gas outlet defines the gas flow directions and with it also the border of the stages.

A double fire gasifier produces

- Product gas with as little tar as a cocurrent gasifier
- Ash with as little carbon as a countercurrent gasifier

But similar to the cocurrent gasifier, the tar content is still not low enough for a direct utilization.

Viking Gasifier In the Viking Gasifier (e.g., [27, 43–45]), the gasification process takes place in three separated zones. These zones are: firstly, a drying zone and zone with pyrolytic decomposition; secondly, a zone with tar removal by partial oxidation and other gas phase reactions; and thirdly, a gasification, especially reduction, zone.



Biomass Gasification for Rural Electrification, Small Scale. Figure 10
Circulating-fluidized-bed gasifier

The drying and pyrolysis zone is designed as a screw reactor. The biomass is transported through this reactor by the screw. The heat for drying and pyrolytic decomposition is transferred through the wall of the reactor. In a plant for electricity generation, mainly the waste heat from the engine can be used for these first process steps and less additional heat is required. The char and the gases leave the reactor at its end. Being a product of pyrolytic decomposition, the gas contains a high amount of tar.

After leaving the screw reactor, the char falls downward and the gases flow downward passing through a free space reactor. In this, air is fed in. The air reacts with the gas, and especially, the tar is removed by

partial oxidation. Additionally other fast reactions in the gas phase take place. The char particles with their low reactivity pass through the free space without being largely involved in these reactions. Because of the exothermal oxidation reactions, the gas temperature increases up to about 1,100°C.

Below the free space in the same reactor, the remaining char accumulates. Flowing through this char bed, carbon dioxide and water-steam in the gas react with the char following the reduction reactions described above. In these endothermic reactions, which generate carbon monoxide and hydrogen, the temperature decreases to about 750°C. The gasification efficiency is increased by the reaction zone,

because thermal energy is converted back to chemical energy.

The Viking Gasifier demonstrates that multistage gasifiers can have some advantages:

- Very low tar content in raw product gas.
- High gasification efficiency especially concerning the use of waste heat for drying and pyrolysis.
- Relatively wet biomass can be used.
- Wastewater is hardly contaminated with hydrocarbons.

On the other hand, the technique is much more expensive than single-stage gasifiers.

FICFB process The FICFB process first realized in Güssing/Austria (e.g., [13, 46–49]) is a dual-bed steam gasification working with two reactors (chambers): one for the gasification process with the gasification agent water-steam, and a second one for combustion for heat supply. The reactor principle is based on a circulating-fluidized-bed reactor. The fluidized bed is used for biomass gasification whereas the recirculation part is designed as a combustion chamber. Biomass is fed into the fluidized-bed gasification chamber where it is converted into nitrogen-free syngas and char using steam as gasification agent. The char and additional raw gas for control purpose are burnt with air in the combustion chamber, heating the accompanying fluidized-bed-particles. The hot bed material is then fed back into the gasification chamber, providing the required reaction heat. There are also further constructions available using the dual-bed principle (e.g., [50–55]).

Dual-bed steam gasifiers are developments specifically for biomass. In the German-speaking area, the FICFB process is at the beginning of commercialization, mainly for CHP applications. Several installations are planned, under construction, or recently started operation. Due the fact that the aspired power range of the FICFB technology is above 2 MW electric power according to about 8 MW fuel input power, this technology is not a small-scale technique. But this technique is important, because commercial operation is almost complete and both the technique and the way for solving the occurring problems are exemplary for other ongoing developments.

Application of the Gas

For the complete utilization of the chemical energy, the fuel has to be oxidized to the highest oxidation number (i.e., to carbon dioxide and water). The product gas is only an intermediate product for simplifying the utilization of the solid fuel. Because here the objective is the generation of electricity, other applications of the product gas (like heat supply, e.g., for industrial furnaces, synthesis of bulk chemicals) are not discussed.

Usually, electricity is generated via mechanical power, which is provided from heat in a thermal cyclic process. Currently, the only alternative of some importance is the fuel cell.

The processes for the generation of electricity from the product gas can be sorted into the following categories:

- Electricity generation via heat (thermal cyclic process) and mechanical power (generator)
 - Processes with internal combustion
 - Reciprocation combustion engine
 - Gas engine (Otto principle)
 - Pilot injection engine (Diesel principle)
 - Gas turbines
 - Processes with external combustion
 - Reciprocation engine (Stirling principle)
 - Externally heated gas turbines
 - Utilization in boilers
- Direct electricity generation from chemical energy (i.e., fuel cell)

Currently, the importance of reciprocation engines with internal combustion in small-scale plants is dominating.

Below, the main options for utilization of product gas from thermochemical biomass gasification for electricity generation are discussed.

Reciprocation Combustion Engine

Reciprocating engines (e.g., [27, 29, 56–59]) are common solutions for the transformation of chemical energy into mechanical power in the low and medium power range. Engines for cars, ships, and block heat and power plants are examples. The main characteristic of reciprocation engines is the stepwise work in strokes.

That is why the combustion does not occur continuously (i.e., in one of several strokes). Most common are four-stroke engines.

Gas Engine (Otto Principle) The basic process steps of the gas engine process are as outlined below:

- Mixing of air and gaseous fuel.
- Intake and compression of an air fuel mixture by the piston.
- Ignition of pressurized air fuel mixture; the ignition in an Otto engine occurs by electrical sparks.
- Combustion of the fuel and expansion of the flue gas; the flue gases move the piston and the piston transfers the power via the conrod to the crankshaft.
- The piston ejects the flue gases.

These steps repeat cyclically.

Gas engines can only be operated with cold gas. Because of the thermal expansion of the product gas at higher temperatures, less mass or less normal volume of gas can be delivered into the cylinders. Therefore, the power of the engine decreases with increasing temperature of the gas [60].

The applicability of a product gas from biomass gasification within a gas engine is mainly determined by three parameters:

- Content of pollutants (e.g., tar)
- Laminar flame velocity
- Methane number

Pollutants can damage the engine. The following components are of high importance:

- Tar could cause coking in high-temperature areas and agglutination in cold areas, especially valves and nozzles are in danger.
- Dust is dangerous because of its abrasive properties and the promotion of dirtying by tar.
- Sulfur compounds and ammonia can reduce the resistance time of the lubricating oil.

The common limits of content for these substances are given in Table 4.

Another main property is the laminar flame velocity. If the flame velocity is high enough, also gases with low heating value can be utilized in gas engines. This is important because product gases from biomass gasification normally have a low heating value especially if air is used as gasification agent.

Similar to the octane number in petrol-fired engines, the methane number is a measure of the antiknock properties. But this can be adapted by using lean-burning (e.g., [8, 61–63]).

Pilot Injection Engine (Diesel Principle) The basic process steps of the Diesel engine process (e.g., [58, 59]) are:

- Mixing of air and gaseous fuel.
- Intake and compression of an air fuel mixture by the piston.
- Ignition of pressurized air fuel mixture; the ignition in a pilot injection engine occurs by an injection of a liquid pilot fuel.
- Combustion of the fuel and expansion of the flue gas; the flue gases move the piston and the piston transfers the power via the conrod to the crankshaft.
- The piston ejects the flue gases.

Biomass Gasification for Rural Electrification, Small Scale. Table 4 Gas quality requirements of the gas utilization processes (values for the orientation) [11, 25, 29, 76–80]

Impurity [mg/Nm ³]	Reciprocating combustion engine	Gas turbine	High-temperature fuel cell	Fuel synthesis (as comparison)
Tar	10–100		0.1–1	0.1–1
Dust	10–50	< 30	1–10	0.02–0.5
Sulfur	1,000		0.1–1	0.01–1
Ammonia	50		0.1–1	0.1–1
Alkali (total)		< 30	0.1–1	0.2–1
Halogens (HCl + HF)			0.01–1	0.01–0.1

These steps repeat cyclically.

There are statements in scientific publications pointing out that pilot injection engines emit much more soot than gas engines.

The gas quality requirements of a pilot injection engine are quite similar to those of a gas engine (Otto principle). A low and fluctuating heating value can be compensated by the injected liquid fuel. Also the requirements to laminar flame velocity are not as strict.

Gas Turbine

Gas turbines (e.g., [64–68]) are common solutions for the transformation of chemical energy into mechanical power in large-scale plants. As opposed to the reciprocation engine principle, all process steps in a gas turbine run continuously but in separated zones of the turbine. That is why the combustion can occur without interruptions.

The basic process steps of the gas turbine process are:

- Air intake and air compression in a centrifugal compressor.
- Injection of pressurized fuel; as fuel clean gases and liquids are possible; if the gaseous fuel is not pressurized, like the product gas from most biomass gasifiers, a separate fuel compression is necessary.
- Combustion under pressure in a combustion chamber.
- Expansion: The flue gases drive an expansion turbine and the mechanical power is available at the shaft.

For small-scale plants, only micro gas turbines are interesting. They are used in several facilities but by far not as often as reciprocating engines.

The use of hot producer gas containing tar is basically possible in gas turbines. But due to the pressurized combustion in gas turbine combustion chambers, pressurized gasification or a gas compression is necessary. Pressurized gasifiers are very seldom realized in small scale. Gas compression is not possible with tar containing gas, and it is not efficient with hot gas. Therefore, gas compression requires gas cooling and tar removal just like a reciprocating engine does. Alkalis are very harmful to the materials used in gas turbines and have to be removed also. Because of the very high velocities in a gas turbine, dust particles cause intensive abrasion. Thus, the content of dust which can be tolerated by a gas turbine is very low.

Common orders of magnitude for the gas requirements are given in Table 4.

The lower heating value of the product gas from biomass gasification compared to natural gas requires an adaptation of the gas turbine.

Processes with External Combustion

Common to all processes with external combustion is the separation of the combustion part and the heat utilization. Only heat is exchanged through solid walls. The material flows in the two parts do not mix.

Stirling Engine A Stirling engine (e.g., [29, 69–73]) is a reciprocating engine with an external heat supply via heat exchangers. Basically, a Stirling engine is composed of a heated operating cylinder, a cooled compression cylinder, and a heat regenerator. The heat regenerator serves for temporary heat storage. The operation gas is enclosed in the engine. Typical operation gases are helium, air, nitrogen, and hydrogen.

Generally, the process steps of the Stirling process are as described below:

- The compression piston pushes the cold operation gas through the regenerator into the operation cylinder. The operation gas is heated in the regenerator and in the operation cylinder.
- The compression piston reaches its dead point. The heating of the operation gas is continued in the operation cylinder, with the operating gas expanding so that the operation piston is moved. The operation piston transfers the power via the conrod to the crankshaft.
- By passing the dead center, the operation piston moves back. The operation gas is pushed through the regenerator into the compression cylinder. The hot operation gas transfers heat to the regenerator. The compression cylinder starts moving back.
- The cooling of the operation gas is continued in the compression cylinder. The compression cylinder continues moving back.

These steps repeat cyclically.

Externally Heated Gas Turbines The principle of the external heated gas turbine is quite similar to that of a gas turbine. Only the internal combustion under

pressure is replaced by a heat exchanger and an external combustion. Being separated from the gas turbine process, combustion can take place at atmospheric pressure. Because the operation gas is only heated and does not react, it is normally recirculated into the process. In this case, the waste heat after the expansion turbine is dissipated by a heat exchanger. In such closed cycle, similar to the Stirling engine, the operation gas may not only be air but also helium, in particular.

Due to the separation of the combustion and the turbine, a lot of different fuels can be utilized. To reach operation gas temperatures as high as in a gas turbine with internal combustions by a heat exchanger is often the weak point of this technology. At such high temperatures, most materials may easily be destroyed.

Gas-Fired Boilers The combination of an uncomplex biomass gasifier and a gas-fired boiler can have advantages compared to biomass-fired boilers. These advantages can be low emissions, very basic boiler design, and the possibility of the fuel shift from gaseous or liquid fossil fuel to biomass. Small-scale electricity generation plants using this combination are very uncommon. But this can be a solution for very dirty gases as produced in waste pyrolysis and waste gasification, or for a fuel shift as part of retrofitting action.

Because of the external combustion and the heat provision via recuperation, gas quality requirements are comparatively low. Basically, every combustible gas can be used in such a plant. Even gas with a very low heating value can be used by utilizing this fuel gas in a hot state for combustion and by preheating the air. When using a suitable combustion chamber, tar can be used along with the gas and simultaneously eliminated during combustion. That is why the tar is only a problem in the equipment before the combustion chamber, especially in the pipes, valves, and nozzles. Therefore, tar containing gas is just to be brought to the combustion and fed into the combustion process in a hot state. The temperature must not be lowered between gasification and combustion.

Further gas quality requirements depend on the emission limits and the used construction materials, because corrosion can be a problem. These factors determine the tolerable content of sulfur and chlorine compounds, for example.

Fuel Cell

Fuel cells (e.g., [74–76]) are devices for the electrochemical generation of electricity utilizing the chemical energy of fuels. The fuels are oxidized in electrochemical reactions, releasing charge carriers. These charge carriers cause a current flow.

Because of the utilization of fuel in a chemical process using catalysts and membranes, the gas requirements of a fuel cell are very high. Not only tar and dust but also catalyst poisons are limited to extremely low values. Nevertheless, projects dealing with the utilization of product gas from gasification exist. Estimates for the gas requirements are given in [Table 4](#).

Gas Treatment

Normally, a gap exists between the fuel gas quality generated by the gasifiers and the gas quality requirements of the gas utilization technologies. Thus, the gas quality delivered from the gasifier ([Table 5](#)) has to be adapted to the requirement of the gas utilization ([Table 4](#)) used in each particular case so as to prevent a deterioration of the gas utilization equipment.

The extent of the necessary gas treatment depends on the techniques used for gasification and gas utilization. For example, a countercurrent gasifier generates gas with a tar content one order of magnitude higher than in the gas produced in other types of single-stage gasifiers, and the gas requirement for some pollutants is several orders of magnitude higher for the use in fuel cells than for a utilization, for example, in gas engines. Different solid fuels used in the gasification can also influence the quality of the raw product gas because of its different content of substances forming gas pollutants. For example, in raw gas from straw gasification, the content of alkalis will normally be higher than in the case of wood gasification.

This means that, for each combination of fuel, gasifier and gas utilization specific demands in terms of gas treatment and suitable gas cleaning technologies exist. Therefore, below common solutions for typical gas treatment tasks are described.

Tar Removal

In most cases, tar removal is imperative to the success of the gas utilization. All single-step gasifiers generate

Biomass Gasification for Rural Electrification, Small Scale. Table 5 Gas quality supplied by the gasifiers (values for the orientation) [11, 32, 76–79]

Impurity [mg/Nm ³]	Fixed bed		Fluidized bed	
	Cocurrent	Countercurrent	Bubbling	Circulating
Tar	10–10,000	10,000–150,000	1,000–30,000	1,000–30,000
Dust	100–8,000	100–3,000	1,000–100,000	8,000–100,000
Sulfur	5–200			
Ammoniac	200–2,000			
Alkali (total)	0,5–5			
Halogens (Hcl + HF)	<500			

tar. And only in the external combustion of hot gas, the tar content is unimportant. High-temperature fuel cells are supposed to be able to use tar containing gas, but the hazard of damage by sooting is obvious.

The tar is a product of the pyrolytic decomposition taking place during biomass gasification. If the tar is not degraded in the following process steps, the tar can be found in the raw gas (Fig. 3). Tar consists of hundreds of different organic species that can add up to an overall tar content of several tens of g/m_N³, for example, in countercurrent gasifiers. During the pyrolytic decomposition, comparatively reactive compounds are generated (so-called primary tars). With increasing temperatures and increasing residence time at these high temperatures, the tar compounds are transformed to more stable substances (so-called secondary and tertiary tars). The content of polycyclic aromatic hydrocarbons (PAH) rises from primary to tertiary tars [6, 81–84].

The main problems with tar are enumerated below [25, 60, 85].

- Tars are condensing on surfaces and leading to agglutination of components. Causative is the high viscosity of the tars. The agglutination will be increased by dust deposition at these surfaces.
- On hot surfaces, tar can easily react, causing sooting.
- Substances contained in the tar, like polycyclic aromatic hydrocarbons, are carcinogenic and toxic.
- Tar is environmentally harmful.
- Being a mixture of hydrocarbons, tar contains a lot of the chemical energy of the fuel.

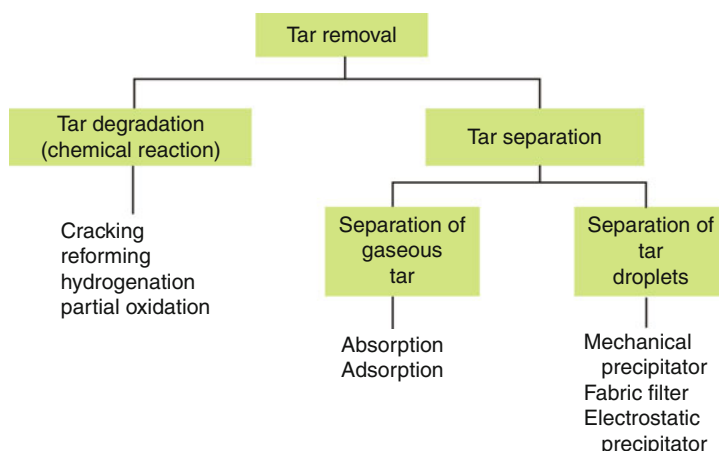
That is why tar removal usually is the most important gas treatment step in electricity-generating plants using gasification.

Because of the specific behavior of tar, being a mixture of organic components and having a condensation range from 100°C to 350°C and more, a lot of different technologies can be used for tar removal. Figure 11 gives an overview.

A differentiation of removal processes can be done between tar separation and tar degradation. The term “tar degradation” summarizes chemical processes which consume the tar by forming simple chemical substances like carbon monoxide, hydrogen, methane, and other simple hydrocarbons. Examples for these reactions are cracking, partial oxidation, steam-reforming, and hydrogenation. Tar separation removes tar out of the gas flow without destroying the tar’s molecules. In this case, tar remains as by-product or waste. Depending on the condensing temperature range, two principles of tar separation exist: Gaseous tar can be separated above the condensing temperature using absorption and adsorption processes. Alternatively, the tar is condensed and removed in a droplet removal unit. Typical units for droplet removal are quite similar to particulate collection systems. Such techniques are, for example, mechanical separators, washers, and electrical precipitators.

A summarizing overview of tar removal techniques is given in Fig. 11 and Table 6 and a comparison in Table 7.

Tar Degradation Processes Tar degradation processes (e.g., [25, 39, 81, 86, 87]) are waste free and



Biomass Gasification for Rural Electrification, Small Scale. Figure 11

Tar removal processes (overview)

Biomass Gasification for Rural Electrification, Small Scale. Table 6 Performance of selected tar removal processes

Technique	Catalytic partial oxidation	RME-scrubber	Electrostatic precipitator	Electrostatic precipitator	Water scrubber
Principle	Tar degradation	Absorption (droplet removal)	Electrostatic droplet removal	Electrostatic droplet removal	Droplet removal (absorption)
Auxiliary material	Air	Biodiesel	–	–	
Tar content raw gas [mg/m _N ³]	4,000–10,000	<4,000	50,000	400	1,000–10,000
Tar content clean gas [mg/m _N ³]	<100	A few	<10	15–35	100–400
Remark	Research	Tested in larger scale	Large scale	Small scale	Small scale

nearly wastewater free and the energy content of the tar can be used. But until today, no sound tar degradation process is available.

Cracking and reforming Cracking is the degradation, normally scission, of organic molecules without a second reacting agent. Its aim is to produce small organic molecules. Reforming means the degradation of organic molecules with water-steam as reacting agent. Target products are hydrogen and carbon monoxide, the most desired gasification products. Because water is contained in the raw product gas, these two reactions occur simultaneously. Both

processes run without catalyst if the temperature is high enough.

Because of the necessary high cracking temperatures of more than 1,000°C which exceeds the gasification temperature, thermal cracking downstream biomass gasification causes an efficiency loss. This makes it an unattractive option for biofuel applications. But this efficiency loss can be compensated by several heat recovery processes.

The other alternative is the use of a catalyst. Catalytic cracking and reforming provide more attractive options in terms of chemical efficiency and process economy. The use of catalytic bed materials, like

Biomass Gasification for Rural Electrification, Small Scale. Table 7 Pros and cons of selected tar removal processes

Tar degradation	Absorption (organic solvent)	Electrostatic precipitator
+ No waste + Less wastewater + No cooling before tar removal + No dirtying before tar removal + High overall efficiency	+ Extensive successful tested + Low raw gas tar content permanent reachable + Commercial available	+ Extensive successful tested + Low raw gas tar content permanent reachable + Commercial available + Experience from coke oven plants
– Research and development topic – Catalysts or high temperature required – Catalyst lifetime	– Treatment of tar waste – Wastewater – Cooling before tar removal essential – Consumption of solvent	– Treatment of tar waste – Wastewater – Cooling before tar removal essential

+ Advantage

– Disadvantage

dolomite, limestone, or olivine sands in fluidized-bed gasifiers, limits the tar content of biomass product gas typically to less than 10 g/m_N^3 . To achieve the required gas purity, further catalytic beds or filters are necessary. Table 1 summarizes the advantages and disadvantages of different catalysts for tar reforming. However, this is a major research and development topic of several companies involved in biomass gasification technology. And so far, these efforts have not reached a development status that makes it suitable for commercial plants.

Catalyst deactivation by sulfur still is a severe constraint for the use of not only Ni-based catalysts but also of a huge number of other highly active catalysts. This problematic underlines the importance of a favorable operating temperature since a sufficient sulfur tolerance of Ni-based catalysts requires temperatures of at least $850\text{--}900^\circ\text{C}$ which can hardly be guaranteed because of the strong endothermic tar and methane decomposition.

Another problem is the catalyst deactivation and destroying by sooting. Especially in the cracking process, soot is produced. Soot is a problem in all tar degradation processes except in partial oxidation, because soot production is the energetically preferred process [88–93]. An overview of catalysts is given in Table 8.

Hydrogenation Because of the hydrogen content in the product gas, hydrogenation (e.g., [94, 95]) of tar is also possible without a feed-in of a reaction agent from outside. In a first step, the molecules will be saturated and functional groups can be removed. Afterward with further hydrogen, a so-called hydro cracking can be performed. In this reaction, the molecules will be cracked into smaller ones. But, in contrast to other cracking reactions, no unsaturated components form, because the hydrogen takes part in the reaction and is intercalated in the formed molecules. In a hydrogenation process, using catalysts with reaction temperatures of about 500°C , 50–80% of the tar can be removed. This process is especially used for the reduction of very high-to-medium contents in a first cleaning step, for example, after countercurrent gasifiers.

Partial oxidation So far in the tar degradation processes described above, the required tar content in clean gas cannot be reached and the catalysts are deactivated quickly. An alternative can be the partial oxidation (e.g. [96–100]). Within such a process, air or oxygen is added to the raw product gas. With these reaction agents, the tar components react, forming carbon monoxide, hydrogen, carbon dioxide, and water. Thereby the gasification, as reaction of a solid fuel generating a gaseous fuel composed of only simple substances, is completed in the partial oxidation. Several configurations with and without catalysts are tested.

Such a catalytic-induced partial oxidation with metal catalyst on metal support reaches 95% tar degradation and a clean gas tar content of less than 100 mg/m_N^3 in a test facility [25, 101–103].

Tar Separation The alternative to tar degradation is tar separation. It can be done either in a gas separation process or by tar condensing and droplet removal. The removed tar contains a high amount of chemical energy and is expensive to dispose. That is why a process internal utilization (e.g., recycling within the gasifier) should be preferred.

Biomass Gasification for Rural Electrification, Small Scale. Table 8 Advantages and disadvantages of different catalytic materials for tar reforming [88]

Catalyst	Advantages	Disadvantages
Calcined rocks (dolomite)	Inexpensive and abundant	Fragile materials and quickly eroded from fluidized beds
	Attain high tar conversion	
Olivine	Inexpensive	Lower catalytic activity than dolomite
	High attrition resistance	
Clay minerals	Inexpensive and abundant	Lower catalytic activity than dolomite
	Less disposal problems	Most natural clays do not support temperatures $> 800^{\circ}\text{C}$
Iron ores	Inexpensive	Rapidly deactivated in absence of hydrogen
	Abundant	Lower catalytic activity than dolomite
Char	Inexpensive	Consumption because of gasification reactions
	Natural production inside the gasifier	Biomass char properties not fixed
	High tar conversion	
Alkali metals	Natural production in the gasifier	Particle agglomeration at high temperatures
	Reduce ash handling problem	Lower catalytic activity than dolomite
Activated alumina	High tar conversion	Quick deactivation by coke
Transition metals	Complete tar reduction at 900°C	Rapid deactivation by sulfur and high tar content
	Increase the yield of CO and H_2	Relatively expensive

Absorption and adsorption processes Tar separation from the gas can be realized by absorption and adsorption processes. Both possibilities are discussed below.

Absorption is defined as a separation process, using different solubilities of substances in liquids. Tars can easily dissolve to be solubilized in several organic solvents such as acetone, tetrahydrofuran, and oils [13, 37, 104]. Because of the properties of the tar, the absorption of tar with a lower condensing temperature occurs normally simultaneously with condensation of other tar components and droplet removal by scrubbing.

Currently, scrubbers with organic solvents (e.g., FAME) as washing solvent are the most common tar removal technologies for small and medium sized biomass gasifiers and are successfully tested at a number of plants. Commercial tar scrubbers are the CTU FAME scrubber [105, 106] used in Guessing and the OLGA tar removal [107–110].

The FAME scrubber is designed for the Guessing gasifier process with a relative moderate tar content of $< 4 \text{ g/m}_N$. In the typical application, a first tar removal is done by a pre-coated baghouse filter operating at 140°C which removes the previously condensed heavy tars before FAME scrubber. Within the scrubber, the incoming gas is cleaned from tars and other organic impurities by initial quenching and subsequent absorption with FAME. The gas leaves the column with a temperature of 10°C . The solvent is regenerated by stripping with CO_2 , but a significant amount of FAME containing the separated tar is fed into the combustion chamber of the dual-bed steam gasifier. Thus, the tar is both, disposed and energetic used. The solution of tar in FAME is much easier to handle than pure tar. Because FAME is also a biofuel, no fossil-based chemical had to be combusted. But FAME is more expensive than the wood fuel, by which it is nevertheless important to save FAME. In the Guessing gasification plant, the FAME scrubber was tested successfully with thousands of hours operating time and is still running. This technique is also successfully used with other gasifier types, especially cocurrent fixed-bed gasifiers [111], but the recirculation of tar is difficult if no separated combustion facility exists.

OLGA is based on a multiple stage scrubber in which the gas is cleaned by proprietary scrubbing oil. In the first section, the gas is gently cooled down by the scrubbing oil. Heavy tar condensates, is collected,

separated from the scrubbing oil, and recycled to the gasifier. In the second stage, lighter gaseous tars are absorbed by the scrubbing oil. The saturated oil is regenerated in a stripper. Hot air is used to strip the tars of the scrubbing oil. This air, loaded with light tars, is recycled to the gasifier for combusting and as fluidization medium. Hence, the stripper column design is not only based upon tar removal, but also upon the amount of air that can be used by the gasifier.

The following two aspects of these systems can be highlighted:

- The OLGA scrubber has very low oil consumption and a lower cooling demand and hence is advantageous in terms of operating costs and GHG emissions.
- The FAME scrubber removes a high proportion of thiophenes and hence lowers the further purification effort.

Adsorption (e.g., [39, 112]) is defined as a separation process, using different adhesion forces of substances on surfaces. Usually, solids with very large specific surface are used as adsorbent. Typical adsorbents for tar separation are activated carbon and charcoal. Because of the properties of the tar, the adsorption of tar with a lower condensing temperature normally occurs simultaneously with the droplet removal by the adsorbent bed acting also as packed bed filter. The capacity for the real adsorption is relatively small; that is why these facilities are often run only as packed bed filter. Therefore, the tar removal rate is often not high enough. If the adsorption really occurs, very low clean gas tar contents are reachable [112]. The charcoal produced by cocurrent gasifiers can be used in these packed bed filters.

So far, no processes for the tar desorption and the reactivation of the activated coal are available. Therefore, the charcoal and the tar have to be burnt. Tar removal systems using fire-proof adsorbents are developed. The tar can be removed from this adsorbent by combustion. What remains afterward is a cleaned adsorbent.

Droplet removal For droplet removal, several techniques are available. But the properties causing agglutination and the high viscosity of the tar are often a problem. Tar can also soil tar removal facilities

(especially droplet separators) or even destroy them. Crucial for the success of these tar removal processes are the complete tar condensation and the formation of precipitative droplets. Practical experience has shown that these two requirements cannot be easily fulfilled.

Mechanical precipitators use the separation of gas and droplets or particles by centrifugal force, for example, in cyclones and impact separators. The conglomeration of droplets into drops, which are easy to separate from gas, enhances the gas cleaning effect [104, 113]. Impact separators have been the common tar removal techniques in wood gasifiers in the middle of the twentieth century and in decentralized gas works [114]. Nowadays, the reachable clean gas in impact separators tar content is not low enough. Other mechanical precipitators are developed, but they are predominantly used as dust collectors [112].

Electrostatic precipitators employ the effect of the separation of electrically charged particles or droplets. In systems which utilize this principle, smallest droplets can be precipitated [113, 115]. Very low tar contents are reachable, if the tar has been condensed before. Gaseous tar cannot be removed in this way. Such precipitators are currently the commonly used tar removal technique in coke oven plants. Small and medium sized constructions have been developed. This technology is another promising tar separation technique besides the scrubbers for absorption [111, 116–118].

For the removal of particles and droplets, a lot of scrubber designs exist (e.g., [39, 81, 112]). Because absorption is not the primary aim, normally water is used as washing agent. But without the effect of absorption, the reachable clean gas tar content is often not low enough. Because of being quite simple, water scrubbers have been the most implemented tar removal techniques in the recent small-scale gasification activities. But especially systems with water scrubbers are problematic if continuous operation is what is aimed at.

Fabric filters are no usual technique for droplet removal. Moisture and, of course, agglutination and high viscous liquids are able to destroy fabric filters within a short time. Nevertheless, so-called pre-coated filters are used for dust removal in tar containing raw gas and particularly for the separation of tar of high condensing temperature [106, 119, 120]. The answer to this

antagonism is the pre-coating. In this process, powders, for example lime stone, are spread on the fabric filter before the operation and during running as often as necessary. Separated dust and liquids remain in this layer. Then the ratio between particles, that means separated dust as well as pre-coating material, to liquid is high enough to hinder the conglomeration of the layer. This mixture can be removed from the filter.

Other Steps of Product Gas Treatment

Dust Removal Another pollutant normally to be removed before the utilization of product gas from biomass gasification is dust (e.g., [39, 112, 115, 121]). Only in some types of combustion chambers for external combustion, dust is supposed to pose no problem. But, in these cases, the dust has to be removed from flue gas because of emission reduction. Especially gas turbines are very susceptible to deterioration by dust.

Generally, most of the common dust precipitators are applicable for biomass gasification such as

- Mechanical separators
- Fabric filters
- Wet scrubbers
- Electrostatic precipitators

The cleaning of the product gas from the gasification of biomass causes several specific conditions for dust removal. Therefore, the facilities have to be adapted. The most important of these conditions are:

- The gas contains water and especially tar. A dust removal system for that application has to be designed to obviate problems with the condensation of water and tar.
- The gas is combustible. Mixtures containing oxygen in a defined ratio can be explosive. That is why, for example, cleaning of fabric filters with compressed-air is forbidden.

If the gas temperature falls below the maximum condensing temperature of the tar, tar droplets and dust particles will be separated together. This has disadvantages and advantages. On the one hand, tar and dust cannot be separately disposed of or used and the dust separation is complicated by liquids as described above. But, on the other hand, only one device for gas cleaning is necessary.

The following applications are frequently used:

- Dust precipitation with fabric filters at temperatures above the tar condensing range. Sometimes this dust precipitation is accompanied by the separation of the tar with the highest condensing temperature in pre-coated filters.
- Separation of dust and tar together in wet scrubbers or electrostatic precipitators.

Other Pollutants Alkali can deteriorate most gas utilizations, especially gas turbines and fuel cells. But it is normally removed simultaneously during the gas cooling and the dust removal. Often it is adsorbed at the surface of dust particles.

Because product gas from wood contains a lower content of halogen and sulfur compounds, these substances are not relevant for the product gas cleaning for the utilization in electrical energy supply. Exceptions are only the utilization in susceptible devices such as fuel cells and the use of nonstandard fuel like straw.

Fuel Gas Cooling and Water Removal In addition to gas cleaning, gas cooling is an important part of gas treatment. As explained, for example, for the utilization in gas engines, the gas temperature has to stay below a limit defined by engine's behavior. The standard solution is cooling with heat exchangers of recuperator design. This makes heat utilization possible. But these heat exchangers can also be affected by pollution with tar.

Alternatively, quench cooling can be employed where cold water or cold organic liquids are brought in contact with the product gas (e.g., by injection of the liquid into the gas).

If the gas temperature goes below the water dew point during the gas cooling, water will be removed from the gas. A separate gas drying is normally not necessary for small-scale applications for electricity production. If water droplets are problematic for the further equipment, a slight temperature increase after the water separation can solve the problem.

Flue Gas Treatment

Flue gases from reciprocating engines often do not fulfill the emission limits for carbon monoxide and hydrocarbons such as benzol (e.g., [27, 56, 58, 59]).

Oxidizing catalysts and regenerative thermal post-combustion are state-of-the-art techniques for the reduction of these emissions.

Overall Process Chains

Based on the components described, a lot of technical possible process chains, which could be operated, can be set up. For this, only a few conditions have to be fulfilled:

- The gasifier must be able to utilize the biomass fed in and to produce only as much gas as the product gas treatment needs.
- The product gas treatment has to adapt the product gas quality generated by the gasifier to the requirements of the gas utilization.
- The gas utilization must be able to generate the required amount of energy.

In addition, a preferable process chain must also fulfill a number of further conditions:

- High efficiency, especially high overall electrical efficiency
- Low financial and technical input
- High reliability
- Low environmental impact
- Others depending on the specific task

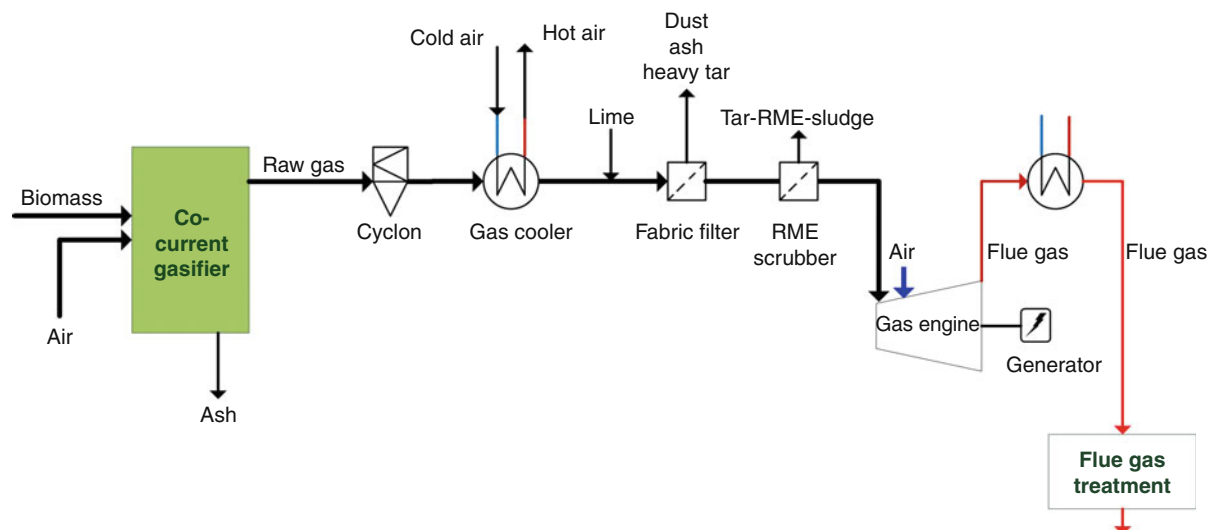
The requirements and operational conditions of gas utilization and gasification determine the necessary additional equipment. In the following, three typical examples for such combinations are explained.

- *Cocurrent gasifier and gas engine*: relatively simple process chain because of relatively clean raw product gas
- *Countercurrent gasifier and gas engine*: complex process chain because of relatively polluted raw product gas
- *Countercurrent and Stirling engine*: simple process chain because of the robust external combustion

Cocurrent Gasifier and Gas Engine

This combination of a cocurrent gasifier and a gas engine (e.g., [119, 120]) is realized in a lot of concepts. The Pyroforce gasification concept is one of the successful examples of the implementation of cocurrent gasification. As shown in Fig. 12, the system consists of biomass supply, gasifier, multistage product gas treatment, gas engine, waste heat recovery, and flue gas treatment.

Applying a cocurrent gasifier, the fuel requirements are quite strict. Only woodchips are allowed to be utilized. The size of pieces has to be between 8 and 63 mm; only 2% fine fraction and 1% coarse fraction



Biomass Gasification for Rural Electrification, Small Scale. Figure 12
Process schema of the Pyroforce process

are tolerable. Also the water content is restricted to 10%. This is the reason why relatively little effort is required for tar removal and handling. The gas treatment consists of a cyclone for the removal of coarse dust, the gas cooling, a pre-coated filter for fine dust precipitation and tar pre-removal, and an FAME-washer for final tar elimination. It has to be considered that this system, which is one of the most reliable small-scale gasification systems available so far, does not use a water washing, but a washing with an organic solvent.

Plants employing the Pyroforce process with an electrical power between 150 and 1,200 kW are running in Austria and Switzerland, where commercial operation has nearly been reached.

Countercurrent Gasifier and Gas Engine

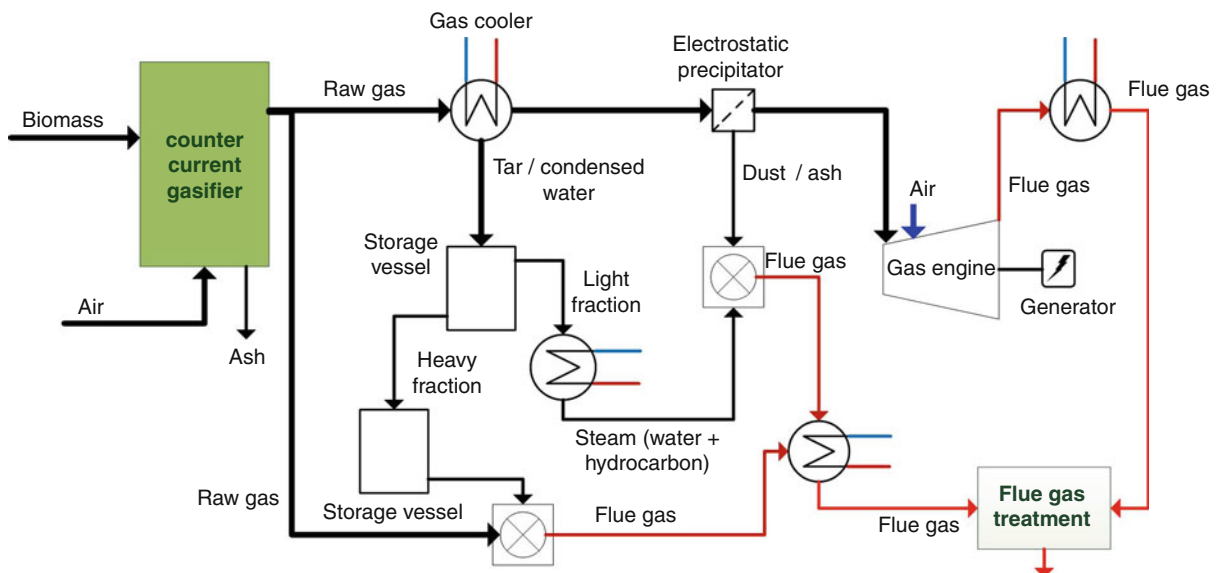
There are also plants operating in practice, which apply a countercurrent gasifier and a gas engine. One successful concept is the Haboøre Updraft Gasification Technology (e.g., [32, 33]). As shown in Fig. 13, the system consists of biomass supply, gasifier, product gas treatment, gas engine, waste heat recovery, flue gas treatment, and extensive condensate treatment system.

Applying a countercurrent gasifier, the fuel requirements are much less strict than for a cocurrent gasifier.

Woodchips with 35–55% moisture content can easily be utilized. Also the use of low-grade woodchips and waste fractions is possible. These and the long time experience are the greatest advantages of this technology.

But the high tar content in the raw product gas of countercurrent gasifiers generates a lot of additional effort. The raw product gas of the Haboøre plants contains, in terms of dry gas, 40–100 g/m_N tar and 70–100 g/m_N³ light hydrocarbons. The raw gas treatment employing a gas cooler with a condensate separator and an electrostatic precipitator is still able to reach a clean product gas tar content of less than 2 mg/m_N³. But the effort for the condensate treatment is enormous. Several systems have been tested. The standard solution applies a separation of light and heavy fractions, a vaporization for the light fraction, separate combustion chambers for the light and heavy fractions (the second one with raw gas as possible additional fuel), and heat exchangers for the use of the heat from the condensate combustion. This condensate treatment is the major shortcoming of this technology.

Plants employing the Haboøre Updraft Gasification Technology are successfully running under commercial conditions in Denmark and Japan. Especially, the plant in Denmark (Haboøre) has proven its practical performance



Biomass Gasification for Rural Electrification, Small Scale. Figure 13
Process schema of the Haboøre Updraft Gasification Technology

in more than 55,000 h of operation. The existing plants are a bit larger than 1 MW electrical output. The gasifier, the gas engine, and also the gas treatment can easily be scaled down. But, the issue of an economical condensate treatment increases with the scale being decreased.

Countercurrent Gasifier and Stirling Engine

The combination with a Stirling engine makes it possible to avoid the problem with countercurrent gasifiers described before. Being a gas utilization technique with an external combustion, the Stirling engine is able to use tar containing gas. In an adequately designed combustion chamber, the tar steam can be burned together with the product gas. The tar reacts to carbon dioxide and water. With it, the tar is a valuable energy carrier. Because the tar is used in the combustion chamber of the Stirling engine, no tar removal is necessary to protect the engine and so the whole process chain can be simplified. But, in addition, tar can be a problem in tubes and other devices before burning.

One system using this combination is the BISEA-system developed in Denmark (e.g., [73, 122, 123]). There are two main problems with this combination:

- The reliability is not proven.
- The efficiency of Stirling engines normally is inferior to the efficiency of gas engines.

Gasifiers of simple design combined with Stirling engines are potential solutions for very small-scale applications, if the reliability of these engines can be improved.

Future Directions

In summary, the gasification of solid biomass is a key technology with great prospects for integration in future energy systems. Especially the performance of small-scale electricity generation, for example for rural electrification, can be enhanced. It can be foreseen that high efficiencies in this scale are only possible by employing gasification techniques. The weak points of this technique are currently a global research topic. These activities suggest that gasification can completely play its potential role in the next few years.

To increase the rate of commercialization, the following research topics have to be executed with an enhancement in efforts:

- Investigation of the detailed chemical processes, especially the reaction pathways and kinetics
- Understanding of the behavior of herbaceous biomass as fuel
- Development of gasifiers which
 - Are able to use different and low-grade biomass
 - Produce gas with less tar and other pollutants
 - Have a high efficiency
 - Are inexpensive
 - Can be operated with less effort
- Development of inexpensive but high-efficient product gas cleaning systems
- Minimization of the amount of waste and wastewater, inexpensive but environmentally friendly systems for their recovery
- Further development of the gas utilization technologies with the aim to use low-quality product gases to decrease the effort of gas treatment
- Enhanced system integration
- Increase in reliability and availability together with a reduction of maintenance and operation requirements

All these activities have to be channeled to create demonstration plants which can prove the reliability, availability, and efficiency of gasification technology.

A current problem is that the research and especially development activities in the field of small-scale gasification are dispersed to many minor and largely isolated players. Of major importance for the future of the technology field of small-scale gasification is to pool their efforts and/or to win a big player for the development of the technology.

An alternative approach to high-efficient rural electrification employing biomass is to produce high-quality fuel from the biomass and to utilize this in specialized, decentralized power generators.

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Biomass Production

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Glossary

Biomass Material derived from recent living organisms.

Bioenergy Energy obtained from fuels derived from biomass.

Bioenergy crops Crops for the production of bioenergy.

Marker-assisted selection (MAS) An indirect selection process in plant breeding. A trait of interest (e.g., shoot biomass) is selected based on a molecular marker (see “molecular marker”), which is linked to the trait.

Molecular marker Molecular markers are identifiable DNA sequences and act as landmarks in the genome. They are inherited by the standard laws of inheritance from one generation to the next.

Trait A genetically determined characteristic or condition. Traits can result from the activity of one single gene or an interaction of the activity of several genes (e.g., shoot biomass is a so-called quantitative trait).

Autotrophic Autotrophic organisms are able to synthesize organic substances from inorganic substances using either light or chemical energy as energy source. These organic molecules are then used to carry out biological functions including

cell growth. Autotrophs such as green plants, algae, and certain bacteria are the starting point of the food chain.

Heterotrophic Heterotrophic organisms depend on the organic compounds synthesized by autotrophs and utilize these organic compounds as food. Heterotrophs are animals, fungi, most of the bacteria and protozoa.

Chloroplast Chloroplasts are cell organelles of plant cells in which photosynthesis takes place.

Enzyme Proteins or protein complexes that catalyze a biochemical reaction.

Photosynthetic efficiency The fraction of incident solar energy reaching the surface of the plant that is converted into chemical energy in the form of carbohydrates.

Stomata Tiny pores of the plant surface necessary for transpiration and gas exchange with the surrounding air; their opening and closing is controlled by various factors such as plant hormones and the water status of the plant.

C3-plants C3-plants use the enzyme Ribulose-1,5-bisphosphat-carboxylase/-oxygenase (RuBisCO) to make a three-carbon compound as the first stable product of photosynthesis. Carbon losses through photorespiration are high in contrast to C4- and CAM plants.

C4-plants C4-plants possess biochemical and anatomical mechanisms to raise the intercellular carbon dioxide concentration at the site of fixation and thus reduce carbon losses by photorespiration.

Crassulacean acid metabolism (CAM) plants CAM plants fix CO₂ during the night, store CO₂ as a component of the compound malic acid, and release it from malic acid during the day. Then it is concentrated around and utilized by the enzyme RuBisCO, thereby increasing the efficiency of photosynthesis. The CAM pathway allows plants to remain their stomata shut during the day, which reduces evotranspiration and allows plants to grow in arid climate.

Photorespiration Photorespiration is a very complex side reaction of the main enzyme of photosynthesis (RuBisCO). The catalytic center of RuBisCO is able to bind CO₂ or O₂ in general the enzyme favors CO₂, but if the level of O₂ is increasing, which occur

if stomata are closed – for example, on hot days to avoid evaporation – the competition between CO_2 and O_2 is increased and more O_2 will bound to the enzyme. Photorespiration leads to a net loss of carbon and reduce the photosynthetic efficiency.

Water use efficiency (WUE) The ratio of photosynthetic CO_2 assimilation and evaporation.

Monocotyledonous plants In the traditional plant taxonomic system, monocotyledonous plants, or monocots, are one of the two major groups of flowering plants the other one are the dicotyledonous plants, or dicots. Most members of the monocots have one cotyledon or embryonic leaf, in their seeds, parallel veins, and floral organs arranged in cycles of three.

Dicotyledonous The second major group of flowering plants – see also Monocotyledonous plants. Members are characterized by two embryonic leaves in their seeds, reticulate veins and floral organs arranged in cycles of four or five.

Harvest index The ratio of grain yield to total plant mass.

Ideotype Ideotypes are defined by breeders, specifying the optimal plant for a particular purpose.

Definition of the Subject

The energy of sunlight reaching the earth exceeds global human energy consumption by a factor of several thousand. Plants are equipped with an intrinsic energy conversion system – photosynthesis – allowing them to utilize sun energy directly for the production of biomass. Human mankind has coevolved and profited from this energy conversion system by placing it at the base of its food production chain and by starting the utilization of firewood as its first energy source. Enormous attempts have been made by mankind to optimize food production from plants via targeted agronomical improvements, such as selection of most productive crop species, increasing agronomical output via the measures of the green revolution and by conventional and marker-assisted plant breeding. In contrast to this, practically no attempts have been made to optimize the use of plant material as energy source because access to fossil – plant-derived – energy resources was far easier. In

a future energy scenario, dedicated production of plant biomass as an energy source will play a vital role, in concert with other sustainable technologies.

Introduction

Renewable resources convert solar energy, the rotation of the earth and geothermal energy into usable energy. Solar power, hydropower, traditional biomass, wind energy, geothermal heat, and biofuels – bioethanol, biodiesel, and biogas – count as renewable resources. Currently, renewable energies supply more than 10% of global total energy consumption with increasing tendency. Fossil fuels supply 388 EJ (ExaJoule; 10^{18} J) per year – this corresponds to more than 80% of total energy consumption – and biomass 45 \pm 10 EJ per year, including traditional biomass usage. The world's primary demand will grow roughly by 1.6% per year to 714 EJ in 2030 [1]. The relevance of bioenergy from biomass differs from region to region depending on the socioeconomical background of the countries: In industrialized countries biomass contributes to less than 10% of total energy consumption; in developing countries this proportion amounts to 20–30%, and in some countries it can exceed 50% (Bhutan 86%, Nepal 97%). In contrast to the developing countries, where traditional biomass (firewood, sometimes dung) is the main energy source for noncommercial usage of the poorer people (cooking, heating), modern bioenergy in industrialized countries is used for industry (heat, electricity), transport (biofuels), and domestic applications (mainly heat). The interest in transport fuels increased strongly in the industrialized countries (North America, Japan, and Europe) as well as within the rapidly developing Asian nations (China and India) and in Brazil. For example, the production of ethanol was doubled from 2000 to 2009 and the production of biodiesel was increased by a factor of 3. In contrast to this, the production of crude oil increased only by 7% [2, 3].

For this energy provision, biomass is needed. This is true for residues and energy crops. The so-called first-generation bioenergy crops were developed from food crops and therefore they compete for fertile land and external inputs with food crops. For bioethanol production, globally relatively few crop species are used (maize, sugarcane, oil palm, rapeseed). These crops

need a high amount of energy input in form of fertilizer and tillage. Thus, they are of limited value from the point of sustainability. For these reasons, new varieties and species were included – the second-generation of bioenergy plants. The aim was to find plants, which do not compete with food crops and which influence the environment in a mitigating and positive manner. Biomass productivity is the result of different factors, which interact with each other: the genetic background of the variety, the environmental conditions, external factors like the grade of rationalization in agriculture, and the local socioeconomic base.

Generation of Biomass in Plants and Animals

Plants are “autotrophic” organisms that live and grow based on consumption of nonliving matter and energy only. They can acquire energy from sunlight via the light-harvesting complexes of their photosystems and use this energy to produce organic matter from mineral nutrients, atmospheric carbon dioxide, and water. As a by-product they generate and release oxygen, thereby facilitating animal life. Hence, the nutrition and generation of plant biomass does not necessarily depend on the interaction with any other organism, although many plants benefit from symbiotic use of other organisms in their vicinity.

Animals and fungi are different. They have never evolved to “take care of themselves,” but they have found successful ways to lead a life and to produce biomass heterotrophically – based on the consumption of dead organic matter. They also have complicated metabolic pathways, converting certain compounds into other compounds. But at the base of these reactions they depend on organic substances (such as carbohydrates, lipids, proteins, vitamins), which have been produced by other organisms and ultimately by plants.

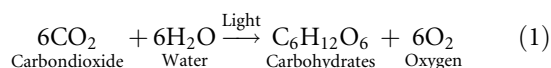
Hence, renewable energy can only be produced in a sustainable and carbon-neutral way mostly from plants. For this reason, this entry will show how plants capture energy from sunlight to produce biomass and it will show the limits and potentials of this process in the context of energy crops for human use. Furthermore, it will elaborate on the ongoing and prospective refinement of plants to quench the human need for food and energy.

Conversion of Light Energy into Chemically Bound Energy

Plants utilize the energy of light quanta to drive biochemical reactions with which they convert anorganic elements and compounds into organic molecules. Both energy conversion (via photosynthesis) and growth processes (via assembly of these organic molecules to biomass) are processes that are characteristic features of plants, which have been optimized in evolution. Intelligent and sustainable production of biomass for renewable energy requires thorough basic process understanding of both processes and directed melioration of photosynthesis and of growth.

Photosynthesis

Photosynthesis converts light energy into chemically bound energy, thereby liberating oxygen from H₂O (to form O₂) and anabolizing carbohydrates from CO₂ and H₂O. Six molecules of carbon dioxide and water are used for the production of one molecule of carbohydrates and six molecules of oxygen. The overall equation for the type of photosynthesis that occurs in plants is shown below (Eq. 1).



The primary process in this conversion of energy from one form into another is the acquisition of photons by chlorophyll molecules, thereby lifting the energy status of chlorophyll molecules to higher levels. These acquisition processes occur in two biochemically distinct regions: Photosystem I and Photosystem II.

The Z-scheme is an energy diagram for electron transfer in the “light reactions” of plant photosynthesis. The y-axis shows an energy scale for each molecule’s ability to transfer an electron to the next molecule, proceeding from left to right. The source of electrons is water (see on the left side). Plants transform light energy into an electron flow and hence into chemical energy in the form of reduced NADPH and adenosine triphosphate (ATP), which are used in the following Calvin-cycle to drive the production of glyceraldehyde-3-phosphate. Thus, the Z-scheme depicts the sequence of electron flow (oxidation and reduction) from the perspective of plant’s energy acquisition. Three major protein complexes are involved

in the Z-scheme: (1) the Photosystem II, (2) the Cytochrome *bf* complex (containing *Cyt_{b6}*, *FeS* and *Cyt_f*, in the middle of the Z), and (3) the Photosystem I (<http://www.life.illinois.edu/govindjee/>). Abbreviations from left to right: *Mn* for a manganese complex containing 4 Mn atoms, bound to Photosystem II (PSII) reaction center; *Tyr* for a particular tyrosine in PSII; *O₂* for oxygen; *H⁺* for protons; *P680* for the reaction center chlorophyll (Chl) in PSII: it is the primary electron donor of PSII; Excited (Chl) *P680* for *P680** that has the energy of the photon of light; *Pheo* for pheophytin molecule (the primary electron acceptor of PSII; it is like a chlorophyll *a* molecule where magnesium (in its center) has been replaced by two “H”s); *Q_A* for a plastoquinone molecule tightly bound to PSII; *Q_B* for another plastoquinone molecule that is loosely bound to PSII; *FeS* for Rieske Iron Sulfur protein; *Cyt. f* for Cytochrome *f*; *Cyt_{b6}* (L and H) for Cytochrome *b₆* (of Low and High Energy); *PC* for copper protein plastocyanin; *P700* for the reaction center chlorophyll (Chl; actually a dimer, i.e., two molecules together) of PSI; it is the primary electron donor of PSI; Excited (Chl) *P700* for *P700** that has the energy of the photon of light; *A₀* for a special chlorophyll *a* molecule (primary electron acceptor of PSI); *A₁* for a phyloquinone (Vitamin K) molecule; *F_X*, *F_A*, and *F_B* are three separate Iron Sulfur Centers; *FD* for ferredoxin; and *FNR* for Ferredoxin NADP oxidoreductase (FNR).

The photosystems are large complexes composed of a number of different pigments and other molecules that are working together in a very clever way to maximize the use of light energy (Fig. 1). The parts of these pigment complexes that do the job of capturing light quanta are called “light-harvesting complexes”; other parts are responsible to initiate biochemical reactions utilizing the energy of a de-exciting chlorophyll molecule while still other parts are responsible to deal with excessive light energy that cannot immediately be transferred to biochemical reactions. Some of the light energy is used in the end to mobilize “ATP-synthase,” a macromolecular protein complex, which is driven by a flux of protons from one side of the membrane to the other and which finally anabolizes the energy-rich molecule adenosine triphosphate (ATP) from adenosine diphosphate (ADP) and phosphate (P) (Fig. 2). ATP is the universal energy currency

of all living matter; decomposing ATP to ADP and P drives a plethora of biochemical reactions in both plants and animals.

The conversion efficiency of these reactions is extremely high. Almost 100% of the incoming light energy can be transferred to the primary steps of biochemical reactions, which is decreased by a number of biochemical “downstream reactions” finally resulting in biomass gain via growth processes.

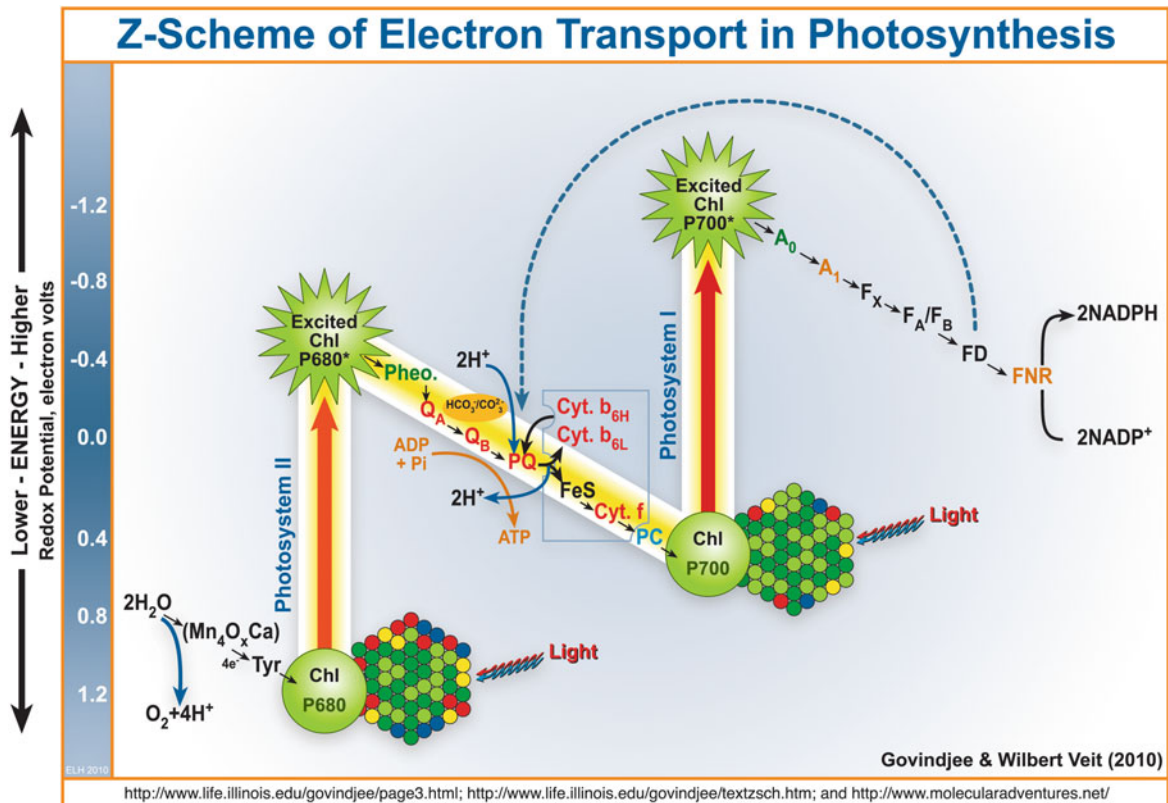
All of the above-mentioned so-called light reactions of photosynthesis (they are driven by the energy of sunlight) take place in the chloroplast. Chloroplasts are organelles contained in each green plant cell. Average leaf tissue contains around 500,000 chloroplasts per mm². The fraction of light energy not used for mobilization of ATP-synthase is providing energy to the so-called dark reactions: The specific biochemical reactions that assemble carbohydrates and oxygen from CO₂ and H₂O (reactions independent of sunlight that can proceed at day or night).

As a central step of these dark reactions, the enzyme Ribulose-1,5-bisphosphat-carboxylase/oxygenase (RuBisCO) captures CO₂ and releases carbohydrates consisting of three carbon atoms, which are later combined to compounds such as sucrose, starch, and cellulose. The core cycle of dark reactions is called Calvin- or Calvin-Benson cycle (Fig. 3). Its core enzyme, RuBisCO is the most abundant enzyme to be found in all organisms worldwide.

This is the core set of processes performed in nature to convert solar energy into the components of biomass providing human mankind with energy and food. This set of processes is performed by all green plant biomass throughout the entire world, both on land and in the ocean. A map of global photosynthetic productivity (Fig. 4) shows impressively that this process embraces the entire globe, with maxima in tropical regions and boreal biomes. Minima are found in polar regions where temperature is too low, deserts, where water is scarce, and certain ocean regions where lack of mineral nutrients imposes shortages on biomass production.

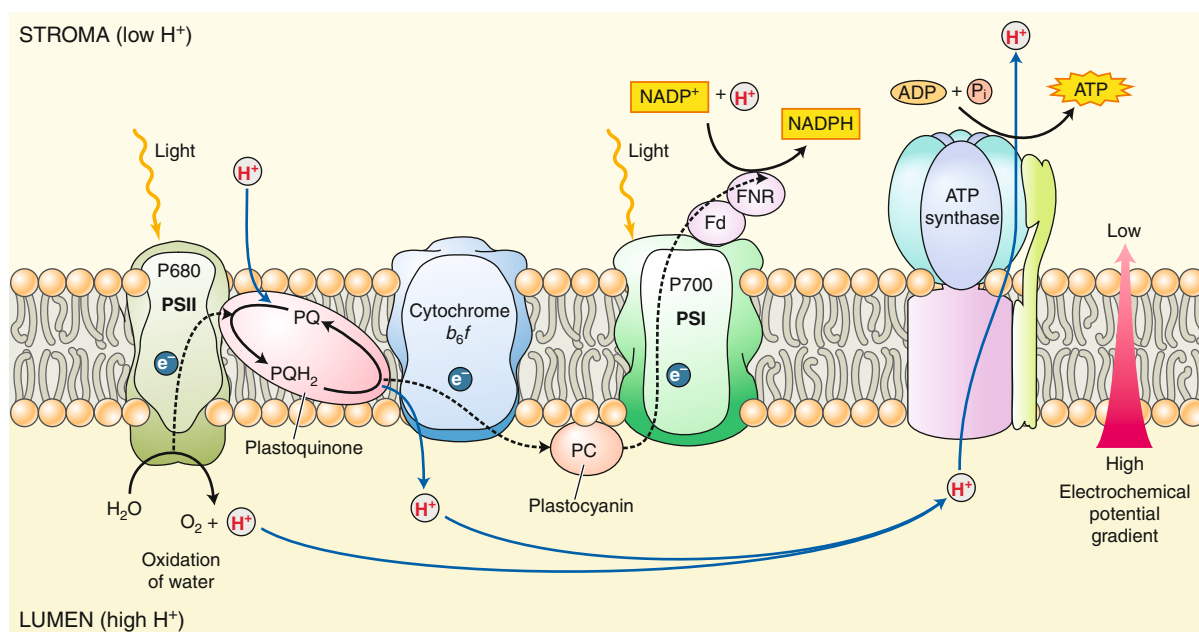
Photosynthetic Strategies in Plants

There are mainly three photosynthetic strategies in plants. They are characterized by differing processes



Biomass Production. Figure 1

The Z-Scheme diagram of photosynthesis shows the electron pathway from water to Nicotinamide Adenine Dinucleotide Phosphate, oxidized form (NADPH⁺); the electrons come from the reduction of water and are used for the production of NADPH. The first Z-Scheme was developed 1960 by Hill [4], many versions of this scheme were developed in the following years. The depicted Z-Scheme was designed by Veit, W. and Govindjee in 2010 (http://www.life.illinois.edu/govindjee/2010_z-scheme.pdf). The Z-scheme is an energy diagram for electron transfer in the "light reactions" of plant photosynthesis. The y-axis shows an energy scale for each molecule's ability to transfer an electron to the next molecule, proceeding from left to right. The source of electrons is water (see on the left side). Plants transform light energy into an electron flow and hence into chemical energy in the form of reduced NADPH and ATP, which are used in the following Calvin-Cycle to drive the production of glyceraldehyde-3-phosphate. Thus, the Z-scheme depicts the sequence of electron flow (oxidation and reduction) from the perspective of plant's energy acquisition. Three major protein complexes are involved in the Z-scheme: (1) the Photosystem II, (2) the Cytochrome b₆f complex (containing Cytb₆, FeS and Cyt_f, in the middle of the Z) and (3) the Photosystem I (<http://www.life.illinois.edu/govindjee/>). Abbreviations from left to right: **Mn** for a manganese complex containing 4 Mn atoms, bound to Photosystem II (PSII) reaction center; **Tyr** for a particular tyrosine in PSII; **O₂** for oxygen; **H⁺** for protons; **P680** for the reaction center chlorophyll (Chl) in PSII; it is the primary electron donor of PSII; Excited (Chl) P680 for **P680*** that has the energy of the photon of light; **Pheo** for pheophytin molecule (the primary electron acceptor of PSII; it is like a chlorophyll a molecule where magnesium (in its center) has been replaced by two "H"s); **Q_A** for a plastoquinone molecule tightly bound to PSII; **Q_B** for another plastoquinone molecule that is loosely bound to PSII; **FeS** for Rieske Iron Sulfur protein; **Cyt. f** for Cytochrome f; **Cytb₆** (L and H) for Cytochrome b₆ (of Low and High Energy); **PC** for copper protein plastocyanin; **P700** for the reaction center chlorophyll (Chl; actually a dimer, i.e., two molecules together) of PSI; it is the primary electron donor of PSI; Excited (Chl) P700 for **P700*** that has the energy of the photon of light; **A₀** for a special chlorophyll a molecule (primary electron acceptor of PSI); **A₁** for a phylloquinone (Vitamin K) molecule; **F_x**, **F_A**, and **F_B** are three separate Iron Sulfur Centers; **FD** for ferredoxin; and **FNR** for Ferredoxin NADP oxido Reductase (FNR)

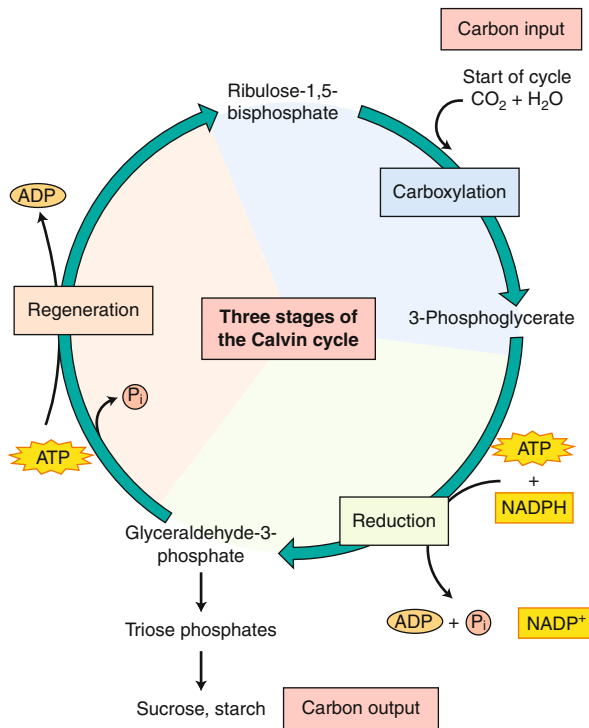


Biomass Production. Figure 2

Light-dependent reactions of photosynthesis at the thylakoid membrane (Taiz and Zeiger, *Plant Physiology*, 4th edition, ISBN 0-87893-856-7). The figure shows the four protein complexes which are part of the electron- and proton transfer. Inside the lumen water is oxidized and protons are released through the Photosystem II (PS II). In the stroma, NADP^+ is reduced to NADPH via Photosystem I (PSI), ferredoxin (Fd) and Flavoprotein ferredoxin-NADPH reductase (FNR). Furthermore the cytochrome b_6f complex transports protons into the lumen, which also contribute to a proton gradient. The movement of these protons along the electro-chemical proton gradient through the ATP-synthase is used to produce ATP on the stroma side. Reduced Plastoquinone (PQH_2) and Plastocyanin (PC) transfer electrons to the cytochrom- b_6f complex and to the PSI respectively

and metabolic pathways of dark reactions. They are called “ C_3 pathway,” “ C_4 pathway,” and “Crassulacean acid metabolism” (CAM). The latter two are specialized and more efficient variations of the basic principles of C_3 photosynthesis depicted above. C_4 and CAM have been evolved in some species by adding some more complexity to the enzymatic machinery and the subcellular localization of photosynthetic processes. C_3 and C_4 plants use different enzymes for capturing the atmospheric CO_2 : C_3 plants use RuBisCo to fix CO_2 from the atmosphere and the first primary product is a 3-carbon organic acid: namely 3-phosphoglyceric acid. In contrast, C_4 and CAM (Crassulacean acid metabolism) use phosphoenolpyruvate (PEP) carboxylase to capture the carbon. Their first photosynthesis products are 4-carbon organic acids: malate and

aspartate. The C_3 pathway is adapted to operate at optimal rates between 15°C and 20°C . The capturing of CO_2 via RuBisCo is temperature dependent: At higher temperature, relatively less carbon is fixed and more O_2 is generated resulting in rather limited growth. Furthermore, under high temperatures stomata (the pores allowing atmospheric air to get in contact with photosynthetic tissue) are closed, thus less CO_2 reaches the chloroplast and the CO_2/O_2 ratio decreases further. In contrast, C_4 plants are adapted to operate at optimal rates under higher temperatures ($30\text{--}35^\circ\text{C}$) and have higher rates of CO_2 exchange; the PEP carboxylase is more efficient in capturing CO_2 independent of temperature, but this way costs more chemical energy in form of ATP. Agriculturally important C_3 species are wheat, rice, and barley. C_4 plants are,



Biomass Production. Figure 3

Overview of the Calvin cycle and carbon fixation. NADPH and ATP which are produced in the preceding light reaction and the oxidative phosphorylation are used to metabolize glyceraldehyde-3-phosphate into hexose sugars which are the primary products of the metabolism and a source of nutrients for heterotrophs. The enzyme RuBisCo catalyzes the carboxylation of carbon dioxide into two molecules of 3-Phosphoglycerate. One molecule is used for the regeneration of the calvin-cycle and the other one for the central metabolic pathway. In different steps, 3-Phosphoglycerate is converted into Ribulose 5-phosphate, which is regenerated to Ribulose 1,5-bisphosphate through a phosphorylation by the enzyme Phosphoribulose kinase. Then the cycle can start all over again (Taiz and Zeiger, Plant Physiology, 4th edition, ISBN 0-87893-856-7)

for example, maize and sorghum. CAM plants are adapted to very dry conditions; they capture light energy during the day with stomata closed. Only during the night, CAM plants, such as cacti, agave, and pineapple, open their stomata and fix CO_2 . Due to this mechanism, they have high water use efficiencies (WUEs) [5, 6]. At a given radiation level, the C_4 species have higher rates of CO_2 exchange than C_3 species: Thus great effort is

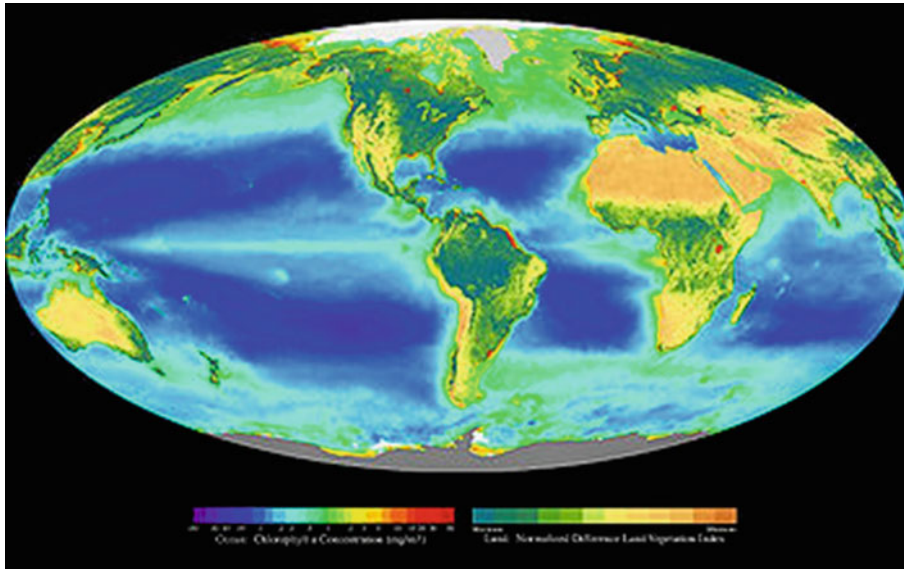
made to engineer C_4 enzymes into C_3 plants, especially into rice [7–9].

The theoretical maximum photosynthetic efficiency – which is the fraction of the incident solar energy reaching the surface of the plant that is converted into chemical energy in the form of carbohydrates present in the differentiated plant tissue – is calculated as 3.3% for C_3 plants and 6.7% for C_4 plants [10–12]. For C_4 plants, this value originates from the following factorial calculation: 100 times 0.5 times 0.8 times 0.28 times 0.4 = 6.7%, where

- The factor 0.5 represents the 50% of photosynthetically active radiation (PAR) of total energy of the solar radiation that arrive at the earth's surface. The wavelengths used by plants are between 400 and 700 nm.
- Eighty percent (factor 0.8) of PAR are captured by photosynthetically active compounds. The rest is reflected, transmitted, or absorbed by non-photosynthesizing material.
- A theoretical minimum of eight photons of PAR are required to convert the radiation energy to glucose [13], which corresponds to 28% (factor 0.28) of the light energy of these photons.
- Finally, 40% (factor 0.4) of the energy stored in photosynthesis are consumed during dark respiration to sustain all metabolic processes of the plant.

C_3 have a lower photosynthesis than C_4 plants due to an additional loss of about 30% of the CO_2 already fixed during photorespiration – a suite of biochemical reactions coupled to the core activity of RuBisCo. Furthermore, the light-utilizing capacity of C_3 plants becomes light-saturated at lower light intensities than for C_4 plants. In consequence, C_3 plants are unable to utilize approximately 30% of the light absorbed by photosynthetically active compounds, thus the maximum efficiency of energy conversion for C_3 plants is about: 100 times 0.7 times 0.7 times 0.067 = 3.3%.

In the field, the average photosynthetic efficiency is often below 1%, due to unfavorable weather conditions, short vegetation periods in the temperate climates, or due to acute biotic and abiotic stresses. As shown above, C_4 plants have higher photosynthetic efficiencies and thus efforts are made to find bioenergy crops in this group in order to increase biomass and yield. Unfortunately, most of the C_4 plants are not adapted to



Biomass Production. Figure 4

Composite image showing the global distribution of photosynthesis, including both oceanic phytoplankton and land vegetation (http://en.wikipedia.org/wiki/File:Seawifs_global_biosphere.jpg)

the temperate zones. In order to adapt C_4 bioenergy crops to colder climates, genetic selection of C_4 plants with improved cold tolerance is necessary (e.g., for maize see [14, 15] and for sorghum see [16, 17]).

Biomass Growth and Metabolism

Still it is not fully clear how photosynthetic efficiency and growth processes interact in detail with each other. The way how environmental factors (light, temperature, water), the genetic structure of genotypes and populations and external outputs (fertilizer, irrigation, tillage) and their interactions – the so-called genetic \times environment interaction – affect photosynthesis, growth, and final biomass is far from being understood; thus a prediction of final biomass from the theoretical maximum of photosynthetic efficiency is difficult at the moment.

At first glance, plant growth seems to be a trivial process. It is easy to understand that a seedling planted in a flower pot can grow better if placed next to a sunny window compared to the seedling left behind in the dark corner of the basement (provided that both received enough water and the same soil). Yet, it is

not possible to explain mechanistically, why the same seedling would have grown much better if it would have been planted in the garden in front of that window at the appropriate time of the year. Plants have evolved not only to withstand a wide range of adverse environmental conditions but also to grow optimally in a certain matrix of dynamically varying environmental conditions to which they are exposed during a typical growth season. Plants are sessile organisms, which has the simple consequence that they cannot escape from unexpectedly cold nights, hot midday hours, dry or wet periods. Moreover, they grow with one half of their body in the atmosphere, being exposed to continually varying light intensity, temperature, herbivore pressure, and other dynamically varying factors – and with their other half in the soil with much more constant temperature regimes but often spatially very heterogeneous supply of water and mineral nutrients. Since their energy and biochemical growth substrates, ultimately provided by photosynthesis, have to be shared between these two parts of their body – the root and the shoot – they are continually facing the dilemma to meet the decision whether to invest into the root or into the shoot, whether to invest the surplus

of energy and metabolites in growth at all or to invest it in storage or in the assembly of more refined, so-called secondary metabolites responsible for protection and defense. Despite the second dilemma, plants need to grow throughout their entire lifetime, since this is their only chance to get access to an increased pool of resources on the background of their sessile lifestyle. Otherwise, their neighbor plants will be faster and steal sunlight, water, or mineral nutrients. The only way out of the constant thrive for increased growth to keep up the success of the plant's body is to invest in "generative growth" – the production of seeds or other forms of offspring that can finally seek their fortune at a different place with less competition or that can endure until times have come that provide better circumstances of living. This prosaic description of the dilemmas, decision processes, and boundary conditions of plant growth and metabolism is far from being put into mechanistic equations, displaying how to engineer the metabolic network of growth processes.

In contrast to photosynthesis, it is not even clear, whether a core pattern of basic principles, such as light and dark reactions in C_3 -photosynthesis, exists for the basic processes of plant growth. In recent years, it could be shown that different plant species and different plant organs grow at different times of the day and with a different spatial distribution of growth activity within growing organs [18–24].

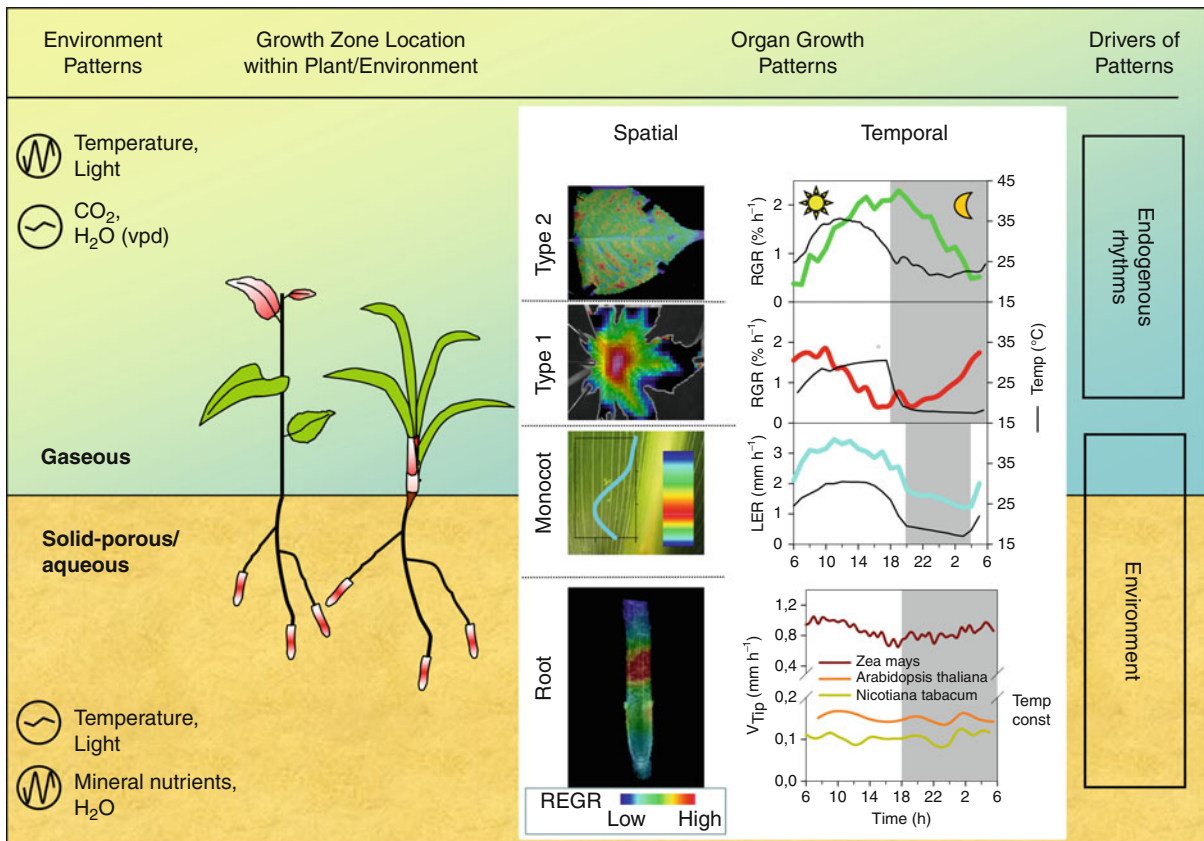
It has long been known that the organization of leaf growth differs strongly between two major groups of higher land plants: the dicotyledonous and the monocotyledonous species [18, 25, 26]. An overview of different temporal growth patterns of monocots and dicots is shown in Fig. 5. Monocot leaves show highest growth rates during the day (white background of right panels in Fig. 5) and growth is often directly linked to air temperature. In leaves of dicot plants, there are two major types of growth cycles differing with respect to their phase (occurrence of maxima and minima during 24 h): Type 1 leaves show maximal growth activity at the beginning of the day and have a base-tip gradient of relative growth rate (RGR) over the leaf. This means that there are higher growth rates at the leaf base and lower growth rates at the tip. *Ricinus communis*, *Nicotiana tabacum*, *Nicotiana attenuata*, and *Arabidopsis thaliana* show this pattern. Type 2 leaves show maximal growth rates at the end of the

day. *Populus deltoides* and *Glycine max* belong to this Type 2. Furthermore, those two species do not show a base-tip gradient.

Only now, it has been realized that the rules, which different species have to follow in order to produce biomass, differ between species in a way that is difficult to predict from prior plant biology knowledge. Only detailed studies of when and where plants grow in certain environmental conditions will allow biologists to understand better the serendipitous pathways of the metabolic processes that lead from some basic molecules produced in photosynthesis to a fully functional plant to be utilized for human purposes.

Plant Selection and Plant Breeding

Breeding aims for improved biomass crops differ strongly from traditional breeding aims for agricultural crops that are the base of human nutrition. The most successful grain crops are derived from wild relatives characterized by huge seeds and an annual life strategy. From the beginning of agriculture on, these crops were produced with higher efficiency compared to other species (less effort for a certain yield), could be stored for a relatively long time and could be improved rapidly due to their short generation time. With the advent of modern breeding methods, the habitus of these cereal plants changed toward varieties with short stems that were able to put an ever higher fraction of their biomass into their seeds, thus increasing their harvest index – the biomass invested in grain or fruit divided by total shoot biomass. In contrast to food crops, bioenergy plants are mainly harvested for their carbon and not for their nitrogen content. Biomass crops of the second generation such as miscanthus and willow contain only one-tenth of nitrogen compared to cereal crops. For fermentation processes, an improved lignocellulosic accessibility to enzymatic degradation is an advantage because this reduces the energy cost of the refining process. A long growing season is an advantage and biomass crops should have low proportional allocation of dry matter content to reproductive structures, thereby having a low "harvest index" in contrast to cereals. In summary, the ideal attributes of crops for biomass production are quite different from the ones of food crops: So-called new plant "ideotypes" are defined



Biomass Production. Figure 5

Different growth patterns of leaves and roots between dicots and monocots. Schematic overview of (from left to right) the relationship between environmental dynamics, growth zone positioning, spatiotemporal growth patterns in leaves and roots, and drivers of growth patterns [18]. *REGR* relative elemental growth rate, *RGR* relative growth rate, *LER* leaf elongation rate, *V_{tip}* velocity of the root tip

by breeders, specifying the optimal plant for a particular purpose. Once the plant model is defined it becomes a breeding target [27, 28]. Searching for new species and varieties such as willow, jatropha, and perennial grasses with new ideotypes is necessary (<http://www.fao.org/news/story/en/item/44142/icode/>). Today's "first-generation" biomass crops come from a limited number of crop species that are not specifically bred for this purpose such as maize, sugarcane, oil palm, and rape seed [29]. These bioenergy crops are not suitable to mitigate the levels of greenhouse gases and global climate change. Moreover, they compete with food crops for land, water, and nutrients. As specified above, new genetic resources have to be exploited and technological

breakthroughs are needed to develop second- and third-generation bioenergy crops, defined by a range of ideotypic traits including improved water-, nutrient-, and light-use efficiencies and improved accessibility of lignocellulose cell wall material to enzymatic degradation. Recent breeding efforts aim to increase vegetative biomass and yield and to improve chemical composition of plant biomass in order to increase conversion efficiency. Many species of this new generation of bio-fuel plants will be adapted to marginal lands that are unsuitable for most food or feed crops [6, 30].

For the breeding of these new species they need to be domesticated; the inter-annual variability of yield must be reduced. The breeding and genetic modification efforts of these second-generation bioenergy

crops are at the beginning compared to that of food crops. Basic breeding programs must include the collection and evaluation of genetic resources, the genetic analysis and development selection criteria, the genetic improvement for biomass yield and energy-related properties [31–33] through classical selection, genetic modification, and marker-assisted selection. Currently different perennial herbaceous species (C_4 grasses like *miscanthus*), woody plants (such as eucalyptus, jatropha, and poplar), and microalgal systems are analyzed [34–39].

Future Directions

Plant biomass is, and could be even more an important contribution to energy production in future. Potential biomass productivity depends on the genetic background of plants, the specific environmental conditions where plants grow, external factors such as the grade of rationalization in agriculture, and also the specific socioeconomic conditions of the countries in which these crops will be cultivated. These factors interact with each other and therefore there is no single strategy for all countries, but still some points are important to be considered on a global level. It is necessary that the production of energy crops is not in competition with food crops for human nutrition. Energy crops need to be produced in an environmentally mitigating manner while at the same time energy consumption during cultivation must be reduced, thereby increasing and energy efficiency of the crop. New species supply a broad range of available genetic material, which could be the base for breeding and selection. There is a lot of room for more efficient production of plant biomass from available resources. The key to utilizing this potential resides in an improved understanding of plant growth processes that generate usable biomass from the first and very efficient biochemical reactions of photosynthesis.

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Biomass Provision and Use, Sustainability Aspects

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Article Outline

Glossary
 Definition of the Subject
 Introduction
 Bioenergy Process Chain
 Sustainability Requirements
 Summary
 Future Directions
 Bibliography

Glossary

Agricultural residues Biomass residues originating from production, harvesting, and processing in farm areas [1].

Bioenergy Energy from biomass [1].

Biofuel Fuel produced directly or indirectly from biomass [1].

Biomass Material of biological origin excluding material embedded in geological formations and/or transformed to fossil. (1) Herbaceous biomass: Biomass from plants that has a non-woody stem and which dies back at the end of the growing season. (2) Fruit biomass: Biomass from the parts of a plant which hold seeds. (3) Woody biomass: Biomass from trees, bushes, and shrubs [1].

Biomass residues Biomass originating from well-defined side-streams from agricultural, forestry, and related industrial operations [1].

Carbon leakages Increase of the Greenhouse gas (GHG) emissions in one country as a result of the climate change mitigation activity in another country by, i.e., relocation of the energy-intensive production to the country with less restrictive environmental law. The opposite situation (reduction of the GHG emissions in one country as

a result of climate mitigation policy in another country), known as spill-over, is also possible [2, 3].

Carbon-rich soils Soils with very high carbon content, such as wetlands, peatlands, etc.

Cereal crops Annual crops grown with the main purpose to use the seed for food production. Some cereal crops (barley, wheat, rye, oat) can be used as a solid biofuel [1].

Certification system The system of assuring the sustainable production of the biomass or biomass fuel.

Climate change Change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties, and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings, or due to persistent anthropogenic changes in the composition of the atmosphere or in land use [2].

CO₂ equivalent (1) Concentration: The concentration of carbon dioxide that would cause the same amount of radiative forcing as a given mixture of carbon dioxide and other greenhouse gases. (2) Emission: The amount of CO₂ emission that would cause the same radiative forcing as an emitted amount of a well-mixed greenhouse gas, or a mixture of well-mixed greenhouse gases, all multiplied with their respective Global Warming Potentials to take into account the differing times they remain in the atmosphere [2].

Energy crops Woody or herbaceous crops grown specifically for their fuel value [1].

Energy forest trees Woody biomass grown specifically for its fuel value in medium to long rotation forestry [1].

Energy (1) Primary energy: Energy forms without technical conversion (e.g., coal, lignite, raw biomass, wind energy). (2) Secondary energy: Energy produced by the conversion of the primary energy carriers (e.g., coal briquettes, gasoline, heating oil, electrical energy). (3) End energy: Energy available for the end-consumer (e.g., heating oil in the oil tank, pellets at the oven, electrical energy before the electricity meter). (4) Useful energy: Energy used by the consumer after the last conversion to satisfy demands such as meal preparation, heating, etc. [4].

Energy efficiency The ratio of energy in the energy carrier to the energy obtained after the conversion.

Fixed carbon Remainder after the percentage of total moisture, total ash, and volatile matter are subtracted from 100 ([1], Adapted from ISO 1213-2:1992).

Forest Defined under the Kyoto Protocol as a minimum area of land of 0.05–1.0 ha with tree-crown cover (or equivalent stocking level) of more than 10–30% with trees with the potential to reach a minimum height of 2–5 m at maturity in situ. A forest may consist either of closed forest formations where trees of various storey and undergrowth cover a high proportion of the ground or of open forest. Young natural stands and all plantations that have yet to reach a crown density of 10–30% or tree height of 2–5 m are included under forest, as are areas normally forming part of the forest area that are temporarily un-stocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest [2].

Fuel Energy carrier intended for energy conversion. Fuels may be solid, liquid, or gaseous, and they may originate from biomass, waste, and/or fossil material [1].

Greenhouse gases (GHGs) Gaseous constituents of the atmosphere (natural and anthropogenic) that absorb and emit radiation at specific wavelengths within the spectrum of infrared radiation emitted by the Earth's surface, the atmosphere, and clouds. Most important GHGs are water vapor (H₂O), carbon dioxide (CO₂), nitrous oxide (N₂O), methane (CH₄), and ozone (O₃), as well as purely human-made GHGs: halocarbons, other chlorine- and bromine-containing substances, sulfur hexafluoride, hydrofluorocarbons, and perfluorocarbons [2].

ILUC Indirect Land Use Change, land use change which occurs outside the production boundary of a feedstock, but which is caused by a change in the use or level of output of that feedstock [5].

Landscapes management residues Residues of woody, herbaceous, and fruit biomass originating from landscape, park, and cemetery management [1].

LUC Land Use Change (usually understood as direct Land Use Change), change of the land cover

(physical and biological cover over the surface of land, including water, vegetation, bare soil, and/or artificial structures) as a consequence of the human activities such as agriculture, forestry, and building construction that alter land surface processes including biogeochemistry, hydrology, and biodiversity [6].

LULUCF Land use, land use change and forestry, a greenhouse gas inventory sector that covers emissions and removals of greenhouse gases resulting from direct human-induced land use, land use change, and forestry activities [3].

Short rotation plants Woody biomass grown as a raw material and/or for its energy value in short rotation plantations [1].

Sustainability The ability to develop in such a way, that the needs of the present are met without compromising the ability of future generations to meet their own needs (Adopted from [7]).

GJ Gigajoule = 10^9 J.

TJ Terajoule = 10^{12} J.

PJ Petajoule = 10^{15} J.

EJ Exajoule = 10^{18} J.

Definition of the Subject

Biomass is the most relevant renewable energy source covering roughly 12% of the global energy demand [8]. It is usually defined as material of biological origin (i.e., plant and animal) on the Earth's surface, excluding material embedded in geological formations and/or transformed to fossil, which is used directly as a fuel or converted into other forms of energy carrier before combustion. Biomass may be also used for its chemical components [1, 9, 10]. Usually one may include in the term biomass trees, crops, algae, and other plants, as well as agricultural and forest residues. Additionally, many materials are considered to be a biomass, such as wastes including food and drink manufacturing effluents, sludge, manures, industrial (organic) by-products, and the organic fraction of the household waste [10]. Other definitions include also ecological aspects of biomass, defined for example as the amount of living organisms per area, habitat, or region [11, 12]. In this entry, the term biomass will be used in the first meaning as a material of the biological origin.

The sustainable use of the biomass has a very strong relevance, since it may offer several advantages, including:

- *Climate and resource protection:* Biomass use helps to mitigate the climate changes, since GHG emissions from its burning are treated as climate neutral. This is due to the fact, that biomass combustion releases approximately as much carbon dioxide, as the plant removed and accumulated during its growth from the atmosphere and the GHG emitted for the biofuel provision are usually of much smaller magnitude compared to the combustion of fossil fuels. Furthermore, satisfying the energy resources with the biomass helps to save the natural, non-renewable energy sources such as coal or crude oil.
- *Supply safety:* Security of energy supply demands reasonable prices for the energy provision and the diversification of sources, which contribute to the supply. Bioenergy is generated from residues and energy crops spread all over the world and therefore increase the security of supply. Additionally, it may support securing the local communities from the fluctuating prices on the global energy markets.
- *Development of the rural areas:* The provision of bioenergy offers the chance to create added value for the local communities (i.e., farmers, small forest owners, manufacturers) and facilitates the development of the rural areas by, e.g., improving the access to cheap and reliable energy.
- *Poverty abatement and local environmental protection:* Through improved technologies to produce heat, e.g., for cooking purpose, it is possible to reduce air pollution and health problems in the developing countries [13]; the use of the biofuels may also help to reduce traffic-related air pollution in megacities (e.g., Mexico city); furthermore, the cultivation of the biomass on the degraded lands may increase land use efficiency and reduce possible negative competition between food and fuels.
- *Export concerns (raw materials, technologies):* Increasing biomass use may be associated with the expanding export possibilities, both for the developing countries (as a source of the biomass material), and for the developed countries (which may

export their resource-efficient, high-tech solutions or ready-to-use products, such as Canadian pellets for co-firing in European power plants).

The sustainability is seen as a precondition for the further development of the bioenergy use, since after the initial phase of the enthusiasm and considering the biomass to be a green source of energy it became clear, that its use may create additional, unintended risks for the environment. Such risks were associated, for example, in the case of GHG emission shifts by using carbon-rich soils to produce biofuels. In this case, the carbon released through the land conversion in South-East Asia usually is balanced by the minimized transport-related CO₂-emissions after very long time [14]. Additionally, increased demand on the biomass has revealed that its use may also cause adverse social, environmental, and economic impacts, such as shortening the food supply in case of increasing the use of agricultural areas for energy crops. In many cases, these effects are occurring indirectly as a result of global market mechanism.

In recent years, two main negative impacts have been recognized, namely indirect land use change and competition with food [15]. As an example of the land use change, one may mention the establishment of the agricultural cultivation areas on high-biodiversity tropical areas as a consequence of increased cultivation of the rapeseed for the biodiesel production. This effect occurs as an outcome of undiminished demand for the animal feed and resulting demand for the arable area. Land use change can be caused by energy crop production directly or indirectly. Indirect land use change occurs, if biomass is produced on established arable land, but the former crop production (food or fodder) from this land shifts to forests or high-biodiversity land [16].

These negative impacts may be avoided by applying the sustainability demands and criteria in the provision and use of the biomass. Therefore, the necessity of the sustainable approach may be seen as a prerequisite for an increased biomass use and a worldwide discussion has started, which aimed at working out sustainability criteria and conditions of the biomass use that would allow avoiding above-mentioned negative impacts. According to the current developments and the policy making trends, meeting these criteria will become the

prerequisite for labeling the biofuels (like bioethanol, hydrogenated vegetable oil) and eventually being recognized by the international and global institutions as the measures toward climate change mitigation [17].

Such criteria of sustainability should address:

- Type of the impacts occurring, associated with environmental, social, and/or economic spheres of human activities related to biomass.
- The spatial and temporal characteristics of the impacts, taking into consideration the entire biomass and bioenergy use chain, including (where applicable) establishment of the agricultural area, harvesting, transport, preparation, conversion, use and disposal phases of the biomass life cycle.
- The consideration of the future developments with regards to risks and uncertainties.

This entry will analyze various aspects of the sustainability of the biomass provision and use, starting from the description of the possible options of the biomass process chain (conversion of solid, liquid, and gaseous biomass energy carriers into heat, electricity, and power) and addressing the necessary sustainability levels. Subsequently, the current and future potentials of the biomass will be discussed, including the most important influencing factors. The last section of this entry will focus on the proliferation of biomass sustainability standards and tools improving sustainability.

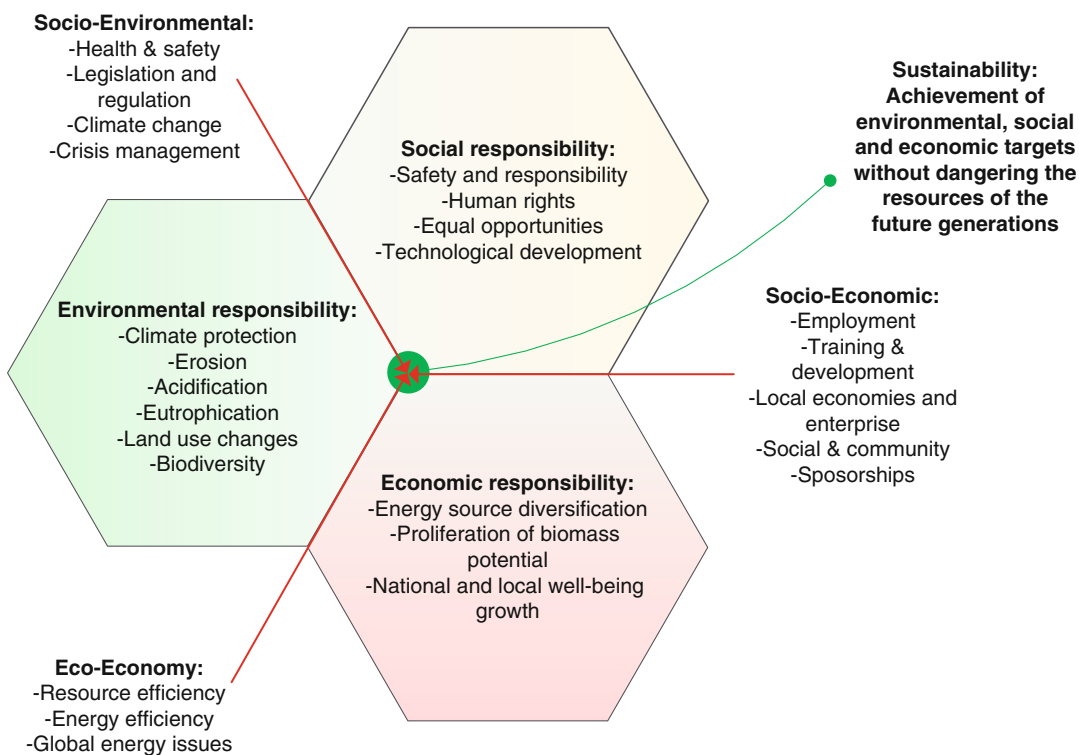
Introduction

The debate about sustainability issues is established since more than 200 years now. The term “sustainability” has been derived from the eighteenth century works of the German nobleman Hanns Carl von Carlowitz, who wrote the handbook on the forestry indicating the need of continuous, steady, and sustained use of the timber resources [18]. Subsequently, the word “sustainable” has been adopted in the English language in the nineteenth century, and finally has being made worldwide known through the reports of the Club of Rome, the Bruntland Commission, and the Earth Summit conference in Rio de Janeiro in 1992 [18].

The modern concept of sustainability is relatively young and still not precisely defined. As a result, there exist many definitions, of which the most

widely known is that created by the Bruntland Commission in 1987 [7]. It states that one may denote sustainability as policies, strategies, and development that meet the needs of the present without compromising the ability of future generations to meet their own needs [7]. This most commonly used definition has been, however, adapted to the needs and points of view of different stakeholders from the public and private sectors. Public stakeholders use the adopted sustainability definition of the Bruntland Commission, namely they define sustainability as the satisfaction of basic economic, social, and security needs now and in the future without undermining the natural resource base and environmental quality on which life depends [19]. The decision makers from the industry underline the minimization of the industry's use of materials and reducing the negative impact on the environment, while increasing long-term shareholder and social value [19]. Both groups recognize, however, the need to support a growing

economy, while minimizing its social and economic costs [19], compare also [20]. Within another idea of the sustainability concept [21] it has been defined that “sustainability means that present and future persons have the same right to find, on the average, equal opportunities for realizing their concepts of a good human life.” Other sources underline, that definitions of sustainability emphasize different aspects of researchers' interests and activities, including ecological sustainability, economic and social sustainability, land restorativeness, environmental soundness, economic viability, social acceptability, sustainability of all agricultural resources, sustainability from the perspective of the political economy and political ecology, as well as energy sustainability [24]. Summarizing the wide range of possible sustainability definitions, the general concept of sustainability denotes measuring and defining the criteria relating to the social, financial, and environmental spheres of life [19, 22] (Fig. 1).



Biomass Provision and Use, Sustainability Aspects. Figure 1

Main areas of sustainability with the special focus on the biomass provision and use (Partially adopted from [23])

Another classification of the various sustainability concepts may be associated with the economy-related perspectives of the weak and strong sustainability. From this point of view, both natural and man-made goods are considered to be a capital. According to the weak concept of the sustainability, both natural and man-made capitals have the same importance and may be used interchangeably. That means that transformation from natural forest to a product (e.g., furniture) does not affect the sustainability, since the future generations may use a man-made capital, which simply substituted the natural capital. The strong sustainability, however, recognizes the unique character of the natural capital, such as clean water, fresh air, and natural landscape. From the perspective of the strong sustainability, it is impossible to substitute lost natural habitats or biodiversity by artificial types of goods [21, 24]. Furthermore, the concept of the weak sustainability is criticized [21] as:

- Being based on the wrong assumptions (i.e., that ecological functions of the environment might be substituted by man-made capital).
- Restricting the right of the future generations to choose the type of capital that is more important for them.
- Assuming that it is possible to substitute the complete and interrelated functions of the complicated ecosystem networks.
- Ignoring the crucial parameters of the human welfare (people want to satisfy not only financial and housing needs, but also lack the contact to the real nature).
- Disregarding the complementarities of several man-made and artificial capitals, such as fishing vessels and fish or sawmills and forests. Thus, disappearance of the natural capital will inevitably mean the termination of the related human activities.
- Rejecting the fact that a minimum stock of natural capital is critical for human survival and well-being, and subsequently missing the possibility of the determination of this critical capital.

The wide perspective and different approaches to the sustainability imply that the use of the biomass does not have to be always sustainable. As an example, the problems related to the indoor air pollution

in the developing countries may be mentioned. Stoves operating with solid biofuels, applied incorrectly and having very low efficiencies, are causing many repercussions to the human health and the environment. As a result, poor societies are suffering from problems caused by toxic air pollution and simultaneously depleting the wood reserves in the vicinity of their residential areas [13]. This example shows, that under some conditions, the biomass might be (at least locally) exhausted or its use might damage the natural environment or human beings. In such way, all three target areas of the sustainability are missed:

- From the environmental point of view, burning wood in such insufficient stoves causes the degradation of the local environment and depletion of the wood reserves for the future generation.
- As far as the social aspects are being discussed, the use of the wood for the cooking purposes is influencing significantly the social status of the women realizing the preparation of the meals; the collection of the wood and the cooking itself takes them in most of the cases between 4 and 6 h per day, therefore leaving very restricted time, i.e., for the education purposes [13].
- From an economic point of view, the wood burned stoves are not sustainable, since the pollution-related problems (e.g., lung diseases) are negatively influencing the well-being level of the communities.

To avoid such negative impacts of the biomass provision and use, many institutions and organizations have tried to establish laws, standards, and regulations, allowing to maintain the status of the biomass as a renewable and sustainable energy source, and to possibly minimize its impact on the natural environment. Sustainability and renewability of the bioenergy sources are being treated in the newest laws and regulations as synonyms. For instance, the United Nations Framework Convention on Climate Change (UNFCCC) recognizes few biophysical conditions, under which the biomass may be treated as renewable and of sustainable origin, namely:

- Sustainable management of the area with respect to especially maintaining carbon stocks and

compliance with the national/regional forestry and nature conservation laws is assured.

- Simultaneously, the land retains its original function (the conversion from croplands/grasslands to forest is, however, being allowed).
- In case of biomass residues, there is no decrease in carbon pools, i.e., there is no use of the dead wood, litter, or soil organic carbon that would cause detrimental change of the carbon pool due to the activity.
- It comes from the non-fossil fraction of the municipal or industrial waste [25].

Despite the fact that there are no any single world-wide accepted standards for sustainability, it is still necessary to take into consideration the scientifically accepted sets of sustainability criteria. There are many institutions and committees that work on such criteria. For instance, the WWF listed the following sustainability standards and certification schemes concerning the biomass sustainability:

- American Tree Farm System
- EUGENE: European Green Electricity Network
- EUREPGAP: Protocol for Fresh Fruit and Vegetables
- FLO: Fairtrade Labeling Organizations International
- FLP: Flower Label Program
- FCS: Forest Stewardship Council
- Green Gold Label Program
- Impact Basel Criteria for Responsible Soy Production
- RSPO Principles and Criteria for Sustainable Palm Oil Production
- Sustainable Agricultural Standards
- SFIS: Sustainable Forestry Initiative Standard
- UTZ Kapeh – Codes of Conduct [26], compare also [27].

In recent years, however, the activities in the development of some standards were stopped due to the difficulties with setting generally applicable rules and the complexity of the overall matter as well as the partly conflicting goals (e.g., EUGENE). Other standards are being criticized for being too general and allowing some non-sustainable biomass sources to obtain the sustainability label. Another problem area within the standard development is the coverage of the important environmental problem fields and their definition [28].

This problem is well visible when, e.g., taking into consideration biodiversity loss or indirect land use change, where no international and scientific agreement so far exists with respect to the methodology or modeling factors that shall be applied.

To overcome the misleading abundance of standards and scopes of application, in recent years, the focus of the development has been put on legal and binding laws, set up by countries, e.g., the USA or international bodies, e.g., the EU. These legally binding acts most probably will set the most widely accepted framework for biomass sustainability criteria. Table 1 presents the synopsis of the most important and commonly mentioned groups of the sustainability criteria.

These standards relate to all three main focus areas of sustainability. The question arises about the implementation of the sustainability in the framework of the biomass use, taking into consideration its possible conversion routes as well as the given technical restrictions.

Bioenergy Process Chain

Today biomass can be used with very different process chains. Basically, such process or provision chains depend mainly on the type of biomass, the available technology, and the respective energy demand. Such high variety of possibilities is caused by the fact that biomass differs in many aspects from other renewable sources of energy: It has a price which determines usually 50–90% of the bioenergy production costs (wind turbine operators do not have to pay for the wind), there are one or more provision and conversion steps needed to provide the bioenergy, and finally, biomass as a resource shows naturally lots of variations [31]. As a consequence, in many cases, different provision chains for the same type of biomass resource are possible. Figure 2 shows a simplified diagram of the possible pathways and conversion of bioenergy carriers with respect to the levels of the sustainability and the related potentials (compare with Fig. 4).

There are three major sources of the biomass: forestry (pulp wood, saw timber, tree rests, etc.), agriculture (straw, energy plants, oilseed crops), and wastes (demolition material, industrial wood, sewage sludge, organic household waste). Depending on the type of input material, the biomass has first to be

Biomass Provision and Use, Sustainability Aspects. Table 1 Example of preconditions of the sustainable development and sustainability indicators (Adapted from [29, 26, 30])

Main focus areas	Sustainability targets, aspects and indicators
Land use, land availability, and land use conflicts	Clarification of land ownership, avoiding negative impacts from bioenergy-driven changes in land-use, priority for food supply and food security
Loss of biodiversity and deforestation	No additional negative biodiversity impacts, avoiding deforestation
Greenhouse gas emissions (GHG)	Minimization GHG emissions, substitution of non-renewable energy sources
Soil erosion and degradation	Minimization of soil erosion and degradation, maintaining carbon stocks
Water use and water contamination	Minimization of water use and water contamination, minimizing emissions affecting eutrophication and acidification
Socio-economic problems and standards	Improvement of labor conditions and labor standards, securing employment, ensuring share of proceeds – wage compensation, avoiding human health impacts, especially with respect to the emissions of particulate matter, NO _x , CO, substances producing summer smog, development of fungal spores
Conservation of the cultural function of nature	Protecting natural values of the landscape
Technical aspects	Reducing energy consumption and increasing the efficiency of energy production

collected and prepared. Since the bioenergy sources are not equally distributed on earth, and simultaneously the supply and demand amounts may be different, the use of the bioenergy very often requires the transportation of the biomass through distances exceeding several thousands of kilometers. In such case, one has to take into consideration also preparation processes for the transport and storage (e.g., in the delivery port).

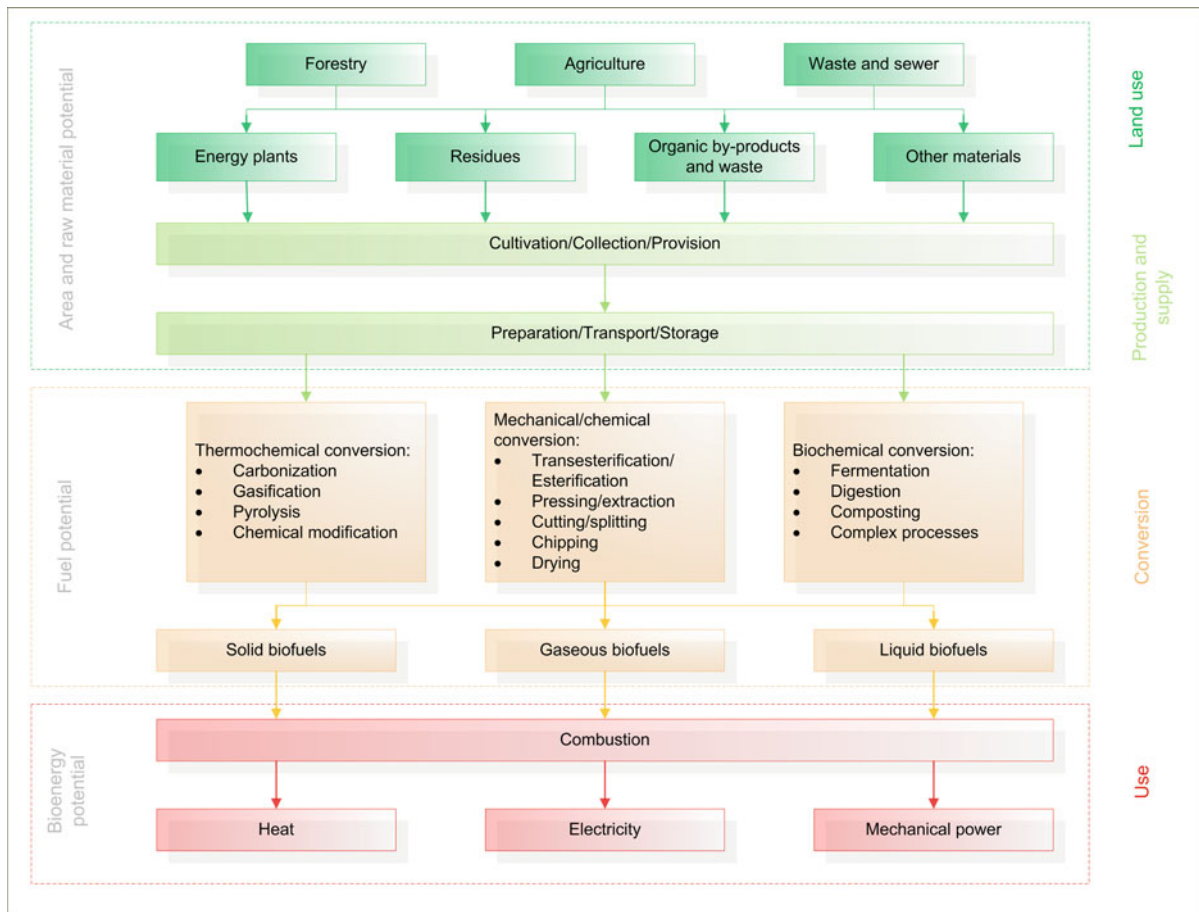
Some of the biomass sources (e.g., demolition wood) may directly be used for energy purposes (usually burned in a furnace). Most of them have, however, to be converted first in order to be used. Here, three basic types of conversion routes may be utilized:

- Thermo-chemical conversion: carbonization, pyrolysis, gasification, or chemical modification
- Physical/mechanical and/or chemical conversion: pressing, extraction, esterification, and transesterification
- Bio-chemical conversion: digestion and fermentation

As a result of these various conversion routes, solid, liquid, and gaseous biofuels are obtained, which subsequently may be burned to obtain heat and/or

generate power (in case of the so-called CHP (combined heat and power), both outputs are possible), and in case of automotive fuels may be used to provide a transportation duty.

Since every technology has some advantages and disadvantages, the continuous improvement of the existing and creation of the new technologies is an ongoing process. As it currently seems, one has to take into consideration not only the obstacles relating to the technical side of the conversion, but also other aspects. One of them is definitely the biomass availability. Not every technology may be technically and economically feasible if there will be not enough supply of bioenergy carriers. Figure 3 presents an overview of the technologies currently available on the market, as well as in the middle and in the long time period, and their respective biomass requirement. According to this, the most promising future technologies, including biomethane from synthetic natural gas (SNG), bioethanol from lignocelluloses, or biomass-to-liquid fuel (BtL), require considerable amounts of the biomass inputs. Additionally, the demand on the capital investment is also substantial, becoming an important obstacle in the technological development.



Biomass Provision and Use, Sustainability Aspects. Figure 2

Main conversion pathways of the biomass resources, simplified (Adapted from [32, 33])

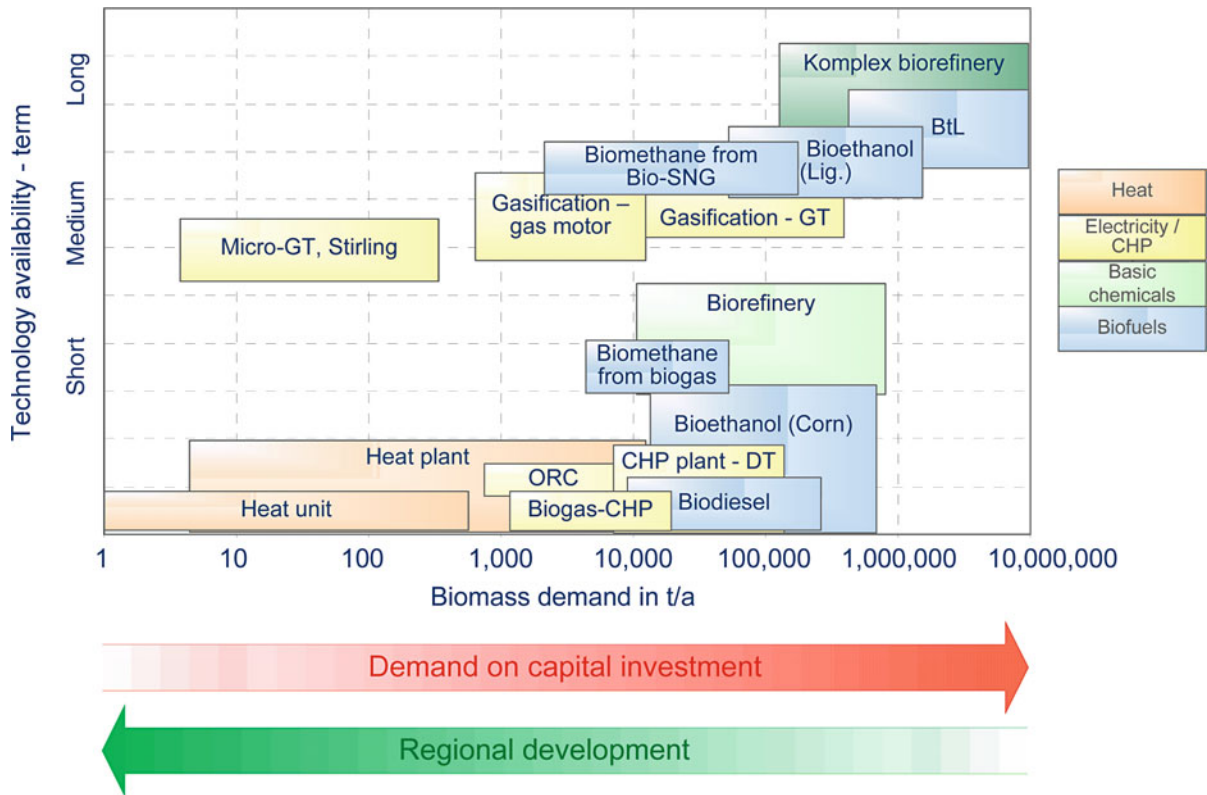
Furthermore, the creation of the large-scale industrial plants is partially contradictory to the idea of the local, sustainable biomass use increasing the well-being of the small communities.

Sustainability Requirements

The rapid development of biomass use especially for energy purposes during the last decade revealed competition for resources which may also affect the sustainability targets worldwide. One example is the food-or-fuel debate, which started in 2007 when both energy and food prices increased dramatically. However, other effects of increased biomass use could be also observed. One example may be the situation of several industry branches which experienced difficulties related to the raw material supply (i.e., pulp, paper, or furniture

industry). The large-scale production of biomass endangers also the biodiversity (through creation of large monocultures for the biofuel production) and disturbs the natural cycles of carbon in the soil or ground and surface water.

Rules to avoid this wide range of the negative impacts need to cover the whole process or provision chain to ensure that there are no leakage effects [35]. This means that sustainability rules have to be applied on the various levels of the biomass processing, starting from the land use, through processing and conversion, to the biomass use (compare Fig. 2). Another relevant aspect is the application of the various sustainability indicators, relating to the land use changes, soil erosion and degradation, acidification, eutrophication, emissions of the greenhouse gases, etc.



Biomass Provision and Use, Sustainability Aspects. Figure 3

Possible conversions technologies with respect to the biomass use, biomass demand, and temporal availability (Adapted from [34])

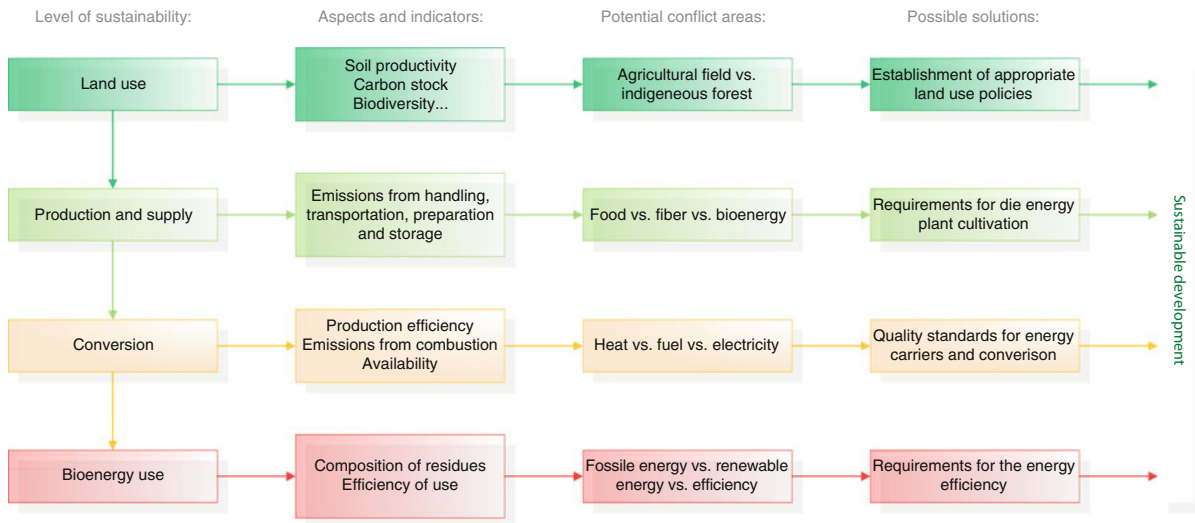
This approach is very complex and can only be introduced stepwise. Thus, it becomes clear that the current discussed European and US-American standards do not fulfill this demand yet, because they focus mainly on the GHG emission indicators, omitting other important sustainability indicators (compare [30, 36]).

Figure 4 shows important aspects of sustainability relevant for bioenergy sources. The entire life-cycle chain of the biofuels has to be taken into consideration, including:

- **Land use:** preservation of all land-based functions (ecological and social: like support of the biodiversity, maintenance of the carbon stock and soil productivity, preservation of the land as the habitat for the local communities, etc.).
- **Cultivation and collection:** Greenhouse gas emissions should be minimized during farmland preparation, sawing, tilling, harvesting, transport,

and collection; additionally, other environmentally damaging emissions should be avoided.

- **Biomass conversion:** Here, the conversion efficiency is a crucial requirement of sustainability considerations; but some other aspects, e.g., health and safety issues, may also play a significant role; furthermore, the use of the biomass resources demands emission reduction technologies for toxic exhaust (e.g., PM_{10} emissions) and strategies for the limitation of, e.g., noise; last but not least sustainable conversion also demands reasonable GHG savings with regard to the fossil reference energies. The reference systems usually relate to the heat, power, and fuels generated from non-renewable fuels like coal, natural gas, or fossil oil.
- **Biomass use:** Since the biomass resources are limited, they must be used effectively and in an energy-saving way; for the overall sustainability, this can be described as following: The importance of



Biomass Provision and Use, Sustainability Aspects. Figure 4

Selected sustainability aspects in relation to the four main pillars of the biomass provision and use (Adapted from [37, 38])

bioenergy for the energy system increases also with a decreasing end energy demand.

- *Residues/ashes*: Remaining materials should be easily integrable in the material flow cycles or (in the case of disposal) inert in the long-term perspective.

Important aspects of the sustainable bioenergy use are discussed in the following sections.

Land Use Change

Recently questions related to land use change (LUC) have become a central part of the discussion concerning sustainability criteria and requirements; this is especially true for the biofuel sector. The term land use change may be defined [39] as environmental change relating to the loss of ecological function, genetic resources, indigenous cultural practices, threatened species' habitats, or even the views and aesthetics of stakeholders, with respect to the given area of consideration. The land-use changes become a critical issue in the discussion about the biofuels, since the intensification of agricultural practices related to the expansion of the biofuels amplified its negative effects on the environment.

Several forms of the LUC have been identified [39], namely:

- Crop changes within agricultural field
- Shift of the fallow land to the cultivation

- Clearing of the natural lands and using them for cultivation purposes
- Displacing of crops from the original areas due to the cultivation of the biofuel crops to the marginal or natural lands

Furthermore, one may identify numerous consequences of the above-mentioned changes, such as loss of habitat for threatened and endangered species or beneficial insects, depletion of the gene reservoirs, increased soil losses through erosion, decreased soil productivity, changes in the hydrological functions of the land (runoff and percolation characteristics), and climate-influencing factors (albedo, evapotranspiration, soil carbon values) [39].

The negative impact of the land use change is relatively well described and quantified in case of the effects occurring in the direct vicinity of the agricultural land (i.e., changes of the carbon stock due to the establishment of the agricultural fields in place of a forest), although such changes (thereafter referred as the direct land use changes, DLUC) have been incorporated in the LCAs of the biofuels recently and basically restricted to the GHG emissions related to the soil carbon release during land conversion [40, 41].

The most controversial discussion in recent years concentrates, however, on the so-called indirect land use changes (ILUC). These changes often are related to

Biomass Provision and Use, Sustainability Aspects. Table 2 Illustrative GHG savings and payback times for biofuel feedstock causing land change [41]

Fuel chain	Assumed country of origin	GHG saving excluding the impacts of land-use change	Carbon payback (years)	
			Grassland	Forest
Palm to biodiesel	Malaysia	46%	0–11	18–38
Soya to biodiesel	USA	33%	14–96	179–481
Sugarcane to bioethanol	Brazil	71%	3–10	15–39
Wheat to bioethanol	UK	28%	20–34	80–140

as the leakage effects, namely, the activity in one place or one country induces the land use changes on the other lands. In this approach, the environmental impacts occur indirectly, outside the boundary of the system in question [39, 40], and thus they are very difficult to assess and to quantify. This difficulty may be related to the spatial (e.g., biomass produced in one location creates pressure on agriculture in other locations) and temporal (e.g., when land cleared for another crop is used for biofuel crop production in successive years) characteristics of the changes, as well as quality of the modeling data [39, 40] and the uncertainty of the results. However, the first modeling approaches have shown that the disadvantages related to the indirect land use changes are causing significant release of carbon stocks. As a result, the GHG savings from the biofuel use are larger than the ILUC-related carbon emissions only after specified time period, so-called payback time (Table 2, [41]).

The large variation of the results relating to the payback times and simultaneously carbon debts (amount of carbon released, that have to be balanced with the GHG savings from the combustion of biofuels) may be seen as a consequence of applying various methods to calculate these quantities, as well as uncertainty of the modeling data. The uncertainties relate to the type, scale, and timing of the indirect effects, and they originate from the following conditions:

- Complex global nature of agricultural markets and uncertainties in predicting the effect of increased production for biofuels.
- Potential for feedstock switching resulting from the possibility of producing the biofuels from various

feedstock; producers may switch their feedstock crops more frequently, which creates a potential danger of the increased land use change.

- Production of co-products.
- Commodity price changes [41].

Several models have been created in order to tackle such a complexity of factors influencing ILUC. Four basic groups of the scientific models have been identified [42]:

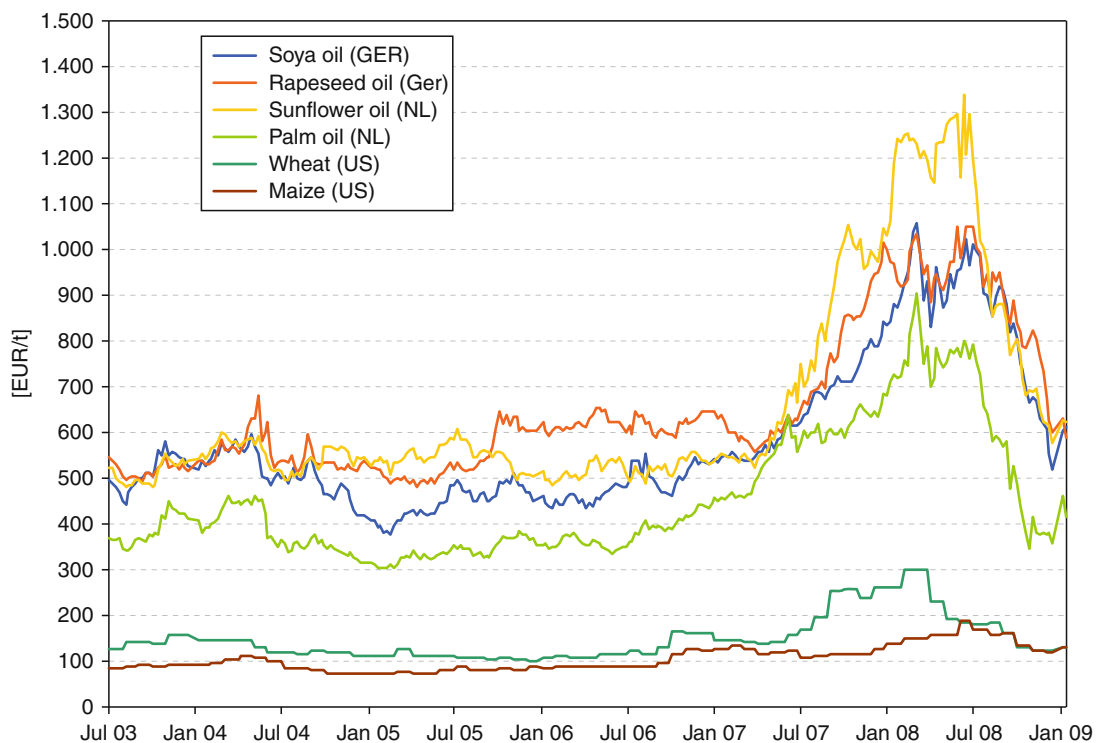
- Complex multi-layered, numeric macro-economic/econometric, and/or biophysical models: Models such as GTAP, FASOM, FAPRI etc., which are primarily used for legislation in the USA (e.g., California). The models calculate the impact of the additional biomass production on the agricultural markets, on the production methods in the agriculture, and finally the dynamics of the land use change.
- Simplified deterministic approaches, such as the ILUC factor or the bonus according to the European Directive on Renewable Energy (2009/28/EC). In these methods, an assumption is being made that additional biomass production by definition results in additional land use. The models allocate proportionally the land use changes to the increased biomass production.
- Other approaches which strike a balance between these two approaches. Here, a simplified schematic calculation of land-use changes and resulting GHG emissions is performed.
- Approaches that focus on ILUC risk minimization with the help of productions methods, which eliminate or reduce the occurrence of negative environmental effects [42].

Depending on the type of the method chosen, the results may vary – even for the identical conversion pathway and input modeling data – considerably. For example, for bioethanol made from the maize, the calculated results span from 30 g CO₂-eq/MJ energy of the biofuel according to the results supplied by the GTAP model, through 36 g CO₂-eq/MJ for the ILUC factor, 50–65 g CO₂-eq/MJ for the FASOM/FAPRI models, up to 104 g CO₂-eq/MJ calculated by the FAPRI model alone [43]. Furthermore, because the indirect effects are occurring outside the economic and political system of one country, it appears to be very difficult to control and minimize these indirect effects. One possible approach is to apply standards and certification systems or incorporation of the sustainability requirements in the laws and regulations, relating to the biomass production in general and very often to the biofuel production. Within the EU, the indirect land use changes have not been quantified in the regulations yet, although the decision makers have recognized the necessity to include them in the

future policy regulations [30]. The US Environmental Protection Agency (EPA) has, however, included ILUC in the newest standards concerning the biofuels, so-called Renewable Fuel Standards (RFS).

One of the most intensively discussed issues concerning the biofuel production recently was the question of the biofuel production impact on the changes of the food prices – so-called food vs. fuel debate – which arose in 2007 when the food prices increased (Fig. 5). A set of main factors responsible for the growing food prices have been identified [44], namely:

- Increased biofuel production driven in the USA and EU by mandates and tax policies, and corresponding demand for biofuel input material: soybeans, maize, wheat, etc
- Rising energy prices
- Declining dollar prices
- Increasing agricultural costs of production
- Export bans and restrictions fuelling the price increase (restricted access to the supplies)



Biomass Provision and Use, Sustainability Aspects. Figure 5

Development of food and biomass prices [45, 46]

- Rapid income growth in developing countries
- Speculative and investor activity

The increase in internationally traded food prices was caused by the confluence of these factors [44]; nonetheless, biofuels played a significant role in this process. However, many studies revealed in the past 2 years a stabilization of the agricultural prices despite constantly increasing share and production of biofuels in the global market. For instance, a recent investigation from the Food and Agricultural Organization (FAO) and the OECD predicts constant, but not sharp increase in the prices during the years 2010–2019. For example the crop prices will be 15–40% higher in comparison to the period 1997–2006, while, e.g., dairy prices will increase by 16–45%. However, biofuel production is not seen as the main factor influencing the prices; other factors shaping the agricultural prices (rising energy prices, demand from developing countries, changes of dietary habits, etc.) are mentioned as well [47]. Nevertheless, from the point of view of the sustainability, one has to analyze and offer solutions, which would minimize the negative impact of the biofuels on the food prices. The problem of the rising food prices may be solved [48], if instead of producing first-generation biofuels (created from the materials which may also be used for nutrition), second-generation biofuels would be introduced into the market. The latter biofuel type is based on crop residues and inedible cellulosic materials, such as leafy steams, stems, stalks, etc. However, the market introduction of second-generation biofuels has to overcome some technical and economic obstacles [48].

Summarizing, the concern about the influence of the biofuel production on the environment seems to be important in the scientific and political discussions. However, blaming the biofuels for the negative effects alone would be too simplistic and would ignore several opportunities created by biofuels, such as bringing particular benefits to the farmers and facilitating the abatement of the poverty worldwide [49]. Nonetheless, attempts to take into consideration and to minimize the possible negative effects were made in the USA with the newest regulations issued by the Environmental Protection Agency (EPA). This regulation, known as the Final Renewable Fuel Standard (also “RFS2”), may be characterized as follows:

- It classifies biofuels on the basis of the life-cycle GHG thresholds as “renewable” (20% GHG savings) or “advanced” (50% GHG savings). Furthermore, for the biomass-based biofuels, a threshold has been set at 50% (renewable biofuels) and 60% (advanced biofuels), respectively.
- “Non-advanced” (renewable) biofuels (mainly corn ethanol) will gain shares until 2022 up to 15 billion gallons (in comparison to the total amount of the renewable biofuel required of 36 billion gallons); then, their blend mandate will remain constant to finally diminish if the technical progress in the advanced biofuels will allow to produce them in larger quantities.
- The EPA’s GHG footprint takes into consideration indirect (in the USA also called “international”) land use change. As a consequence of this approach, the initial GHG savings of corn ethanol of approximately 52% were reduced to the level of 21%, which not surprisingly become immediately an disputable matter for various groups of interests, such as farmers, fuel producers, investors, and industry players, as well as politicians trying to stop or at least delay applying the ILUC approach within the ongoing decision-making process [50, 36, 51].

For the calculation of the indirect land used changes, a combination of the complex mathematical models have been applied, including remote sensing techniques, based on the historical data (Table 3).

Most of the aspects covered by these models have a significant effect on the final result. But the calculated numbers are still characterized by high uncertainties. Nevertheless, the results are comparable in a better way than those gained with individual approaches [36].

The US Environmental Protection agency has based the assessment of the ILUC on the foundation of the so-called Wheel-To-Wheel (WTW) Life Cycle Assessment (LCA), including each stage of the biofuel production, such as production or extraction of the feedstock, feedstock transportation, fuel production, fuel transportation and distribution, as well as tailpipe emissions. Furthermore, the EPA has made a decision to use a consequential LCA, not the attributional one.

- The attributional LCA provides the information about the emissions and environmental impacts caused by the product or service, emitted during

Biomass Provision and Use, Sustainability Aspects. Table 3 Models and data used for the calculation of the ILUC within RFS2 [42]

Acronym	Name of model	Type of model
DAYCENT		Biophysical model for soil processes
FAPRI	Food and Agriculture Policy Research Institute	Partial equilibrium model (soil)
FASOM	Forest and Agriculture Sector Optimization Model	Partial equilibrium model (USA)
REET	Greenhouse gases, Regulated Emissions, and Energy use in Transportation Model	Life-cycle model for emissions from the transportation sector
MODIS	Moderate Resolution Imaging Spectroradiometer	Satellite data on land use/cover
MOVES	Motor Vehicle Emission Simulator	Model for vehicle greenhouse gas emissions

B

its life cycle. The processes taken into consideration are linked in a straight line to the product or service in question by material, energy flows, or services following supply-chain logic. In this type of the LCA, land use impacts are typically confined to direct impacts (e.g., environmental consequences of converting forest areas for the production of corn used within the ethanol production) [36].

- A consequential LCA, however, accounts the GHG emissions or other environmental impacts related to the product or service indirectly, occurring as a consequence of the changes in the demand of the product or service. Here, the changes in the GHG emissions are identified by linking the causes with the effects. For example, if the production of ethanol in the USA increases, the biofuel production may be exported to abroad. As an effect, additional corn or grain production in South American countries has to take place, resulting in, i.e., destroying rain forest for the purpose of establishment of new agricultural fields in Brazil. As a consequence, initial GHG saving by the production of bioethanol will be diminished by cutting off the forests in Amazonia.

The EPA has chosen the consequential LCA as a main research method, since the US administration has decided to take into consideration not only the direct GHG emissions, but also the significant indirect emissions being the effect of the land use changes. Furthermore, the full fuel life cycle has been modeled, including all stages of the fuel and feedstock

production and distribution, as well as its use. The Global Warming Potential was estimated using the mass values of the greenhouse gases [36].

The methodology of the RFS2 rulemaking was based on mathematical models created for various purposes. In general, these models have taken into consideration the data estimated for nine land categories in 750 regions across 160 countries worldwide, with a weighted average applied to the rest of the world, covering all significant agricultural producers. The scientific basis for the models was the Economic Input–Output Life Cycle Assessment (EIO-LCA), which estimates the materials and energy resources required for, and the environmental emissions resulting from activities in the overall economy. Furthermore, the following models, modeling factors, approaches, and methods were combined together, in order to obtain comprehensive and reliable results with respect to the various areas of science, needed to estimate ILUC:

- Forestry and Agricultural Sector Optimization Model (FASOM): estimation of the changes in the US agricultural and forest sectors (e.g., changes in crop acres resulting from increased demand for biofuel feedstock or changes in the number of livestock due to higher corn prices) and their associated emissions, as well as land use shifting between crops, and interactions with pasture, and forestry; partial equilibrium economic model.
- Greenhouse gases, Regulated Emissions, and Energy use in Transportation (REET): spreadsheet analysis tool developed by Argonne National

Laboratories for calculation of the GHG emission factors for fuel and fertilizer production.

- IPCC guidance factors: livestock GHG emission factors.
- CENTURY and DAYCENT: models developed by the Colorado State University to estimate US impacts of the N₂O emissions from the fertilizer application; DAYCENT simulates plant–soil systems and is capable of simulating detailed daily soil water and temperature dynamics and trace gas fluxes (CH₄, N₂O, NO_x, and N₂); CENTURY as a generalized plant–soil ecosystem model simulates plant production, soil carbon dynamics, soil nutrient dynamics, and soil water and temperature.
- Integrated Food and Agricultural Policy and Research Institute international models, as maintained by the Center for Agricultural and Rural Development (FAPRI-CARD): estimation of the impacts of biofuels feedstock production on international agricultural and livestock production; the models capture the biological, technical, and economic relationships among key variables within a particular commodity and across commodities relevant, e.g., for the ILUC.
- Satellite data: used to analyze recent land use changes around the world that have resulted from the social, economic, and political forces that drive land use; EPA has made the assumption that these recent drivers of land use change will remain in relative effect through 2022 modeling time frame such that the recent trends in land use change are indicative of land use changes likely to result in 2022 due to biofuel production; furthermore, the recent land use change patterns were combined with various estimates of carbon stocks associated with different types of land at the state level.
- IPCC Agriculture Forestry and Other Land Use (AFOLU) Guidelines and Winrock International organization: land use change emissions factors [36].

Summarizing, the US EPA has estimated the ILUC on the basis of the economic input–output models. The results of the calculation were combined with the satellite data in order to predict the types of the land converted to cover the increased land demand resulting from the biofuel production. The measurement of the ILUC was done with the help of the GHG emissions,

calculated for different types of the land converted. As the EPA underlines, the results of this assessment are characterized with some level of uncertainty which, however, has been taken into consideration and incorporated in the final results of the analysis [36].

The uncertainty of the modeling data and results as well as the complexity of the ILUC issues and factors that have to be taken into consideration are creating the questions about the real impacts of the ILUC and whether or not ILUC should be taken into consideration when setting policy objectives and targets. As already mentioned, ILUC effects are only mentioned but not implemented in the current EU regulations. In the USA, they become a part of the RFS2 standard, but the inclusion of the ILUC as well as the calculated ILUC-related GHG emissions has been extensively criticized. Certainly, the criticism from the farmers and lobbying groups representing industry branches investing and offering, e.g., bioethanol plants may be well understood. However, the critical considerations about the nature and quantification of the ILUC are also noticeable in the scientific discourse. The inclusion of ILUC in GHG balances on the basis of the LCA technique of biofuels is an ad hoc solution to the more fundamental problem of unsustainable agricultural practices in many parts of the world [52]. Furthermore, critics of the ILUC underline that ILUC application in the policy-making process penalizes those that cannot affect the course of land use change while providing no incentives to those that could. The scientific and political debate should concern rather “food vs. feed” instead of “food vs. fuel” debate [53], since about 90% of the human use of arable land is to produce animal feed mostly for the beef cattle. Therefore, the debate should be focused more on the dietary habits and could be also called “beef vs. barrels” debate. Furthermore, the complexity of the models impedes the clarity of the results and the possibilities to check and correct them, if necessary [53]. One has to mention that the criticism of the ILUC incorporation is especially strong in the USA, where the indirect effects were incorporated in the existing standards. Within the EU, on the contrary, scientists and decision makers do not question the nature and existence of the ILUC effects, but focus more on the methods to quantify and subsequently include them in the decision-making process and the binding regulations.

Efficiency

Although the ILUC has drawn a public attention in the last few years and influenced even the legally made thresholds levels for the biofuels in the USA, the land use changes may not be seen as the only one and the most important criterion of the biomass sustainability. A survey among 46 experts being active in the field of the bioenergy in different regions of the world has been carried out [54], asking about the opinion about the most critical sustainability criteria. These 35 criteria mostly mentioned represented social, economic, and environmental spheres of life in the ratio 4:1:4, respectively. The ten most important criteria, obtained from the survey analysis, are presented in Table 4.

As one can see, the efficiency (represented directly and indirectly in several above-mentioned factors) characterizes the crucial part of the sustainability indicators. Simultaneously, increasing the efficiency is the easiest and most feasible option to increase sustainability of biomass and decrease GHG emissions [55]. Therefore, for further consideration, the following sustainability criteria and indicators will

be described in detail with respect to the biomass and bioenergy: GHG balances and GHG-saving efficiency, area efficiency, material efficiency and efficiency of use.

In many cases, the various types of efficiencies are strongly related to each other (i.e., material efficiency and GHG reduction efficiency). In some cases, several types of efficiencies may be even combined in one term. For example, the heads of the European Environmental Agencies have defined “resource productivity” as the efficiency, at which energy and materials are used throughout the economy [56]. However, in most of the cases, the political decisions in the field of biomass use are setting targets with respect to the energy and GHG saving efficiencies.

Biofuels are often used in a very unsustainable and inefficient ways mostly due to the lack of capital for the investment in the modern equipment [55]. This fact is easily observed in developing countries, where biomass resources are utilized mainly for cooking and heating purposes. In these countries, increasing the efficiency of fuelwood use would have significant positive effects

Biomass Provision and Use, Sustainability Aspects. Table 4 Identified sustainability criteria and their short description (Adopted from [54])

Rank	Sustainability criterion	Description
1.	Greenhouse gas balance	GHG balance of system covering CO ₂ , CH ₄ , O ₃ , NO ₂ , H ₂ O
2.	Energy balance	Conversion efficiencies, energy return on investment, energy return per hectare
3.	Soil protection	Impacts on soil fertility, changes in nutrient cycling, rooting depth, organic matter, water holding capacity, erosion
4.	Participation	Inclusion of stakeholders in decision making; facilitation of self-determination of stakeholders
5.	Water management	Surface and groundwater impacts, riparian buffers, irrigation and cooling cycles and waste water management
6.	Natural resource efficiency	Efficient use of resources at all stages of the system
7.	Microeconomic sustainability	Cost-efficiency incl. start-up costs, internal rate of return, net present value, payback period
8.	Compliance with laws	Complying with all applicable laws and internal regulations like certification principles, countering bribery
9.	Ecosystems protection	Safeguarding protected, threatened, representative, or other valuable ecosystems (e.g., forests); protecting internal energy fluxes/metabolism
10.	Monitoring of criteria performance	Monitoring systems in place for all criteria (e.g., leakage or additionally in GHG accounting)

on greenhouse gas emissions, could reduce the unsustainable exploitation of the natural resources, as well as it may have a positive effect on the indoor air quality. Furthermore, the following categories of GHG emission reductions due to the increase of the energy efficiency have been identified:

- CO₂ emission reductions related to energy inputs into the fuel cycle, mostly during the production and conversion stages.
- Non-CO₂ emission reductions related to end-use efficiency and conversion. In this emission category, increasing the efficiency of, e.g., fuel stoves can result in significant reductions of other pollutants, including non-CO₂ greenhouse gases (CH₄) and other ambient air pollutants, particularly the emissions of unburned components such as VOC (volatile organic compounds), PAH (polyaromatic hydrocarbons), carbon monoxide, and NO_x.
- Land use-related emission reductions (which make up the bulk of GHG emissions from current biomass energy systems) and additional benefits.

In general, the rules implemented in the USA and EU set defined GHG reduction efficiencies as a prerequisite to recognize biomass source (especially valid for the liquid biofuels) at certain defined levels. For the EU, these values vary from 35% to 60%, and for the USA from 20% to 60% (depending on the time frame; the latter values are intended for the advanced biofuels of the next generations introduced around years 2017–2022).

An important remark has to be made with respect to the methodology of accounting the GHG emissions when burning biomass sources. Usually, the renewable sources are considered to provide carbon neutral energy, because the carbon dioxide emissions emitted during combustion are being a part of the natural cycle. As a consequence, re-growing biomass captures the CO₂ emissions released during the combustion. However, the GHG emissions of the biomass burning in the life-cycle perspective may be higher than those in case of the fossil fuel burning; the excess of the emissions is called carbon debt. The numerical value of this debt may depend on various factors, such as type of the energy generated, type of the fossil fuel being displaced (question of the reference system), or the management

practices applied when producing the biomass. The difference between the carbon debt, direct GHG emissions, and accounting on the life-cycle basis may lead, however, to misleading interpretations, if oversimplified or interpreted without in-depth analysis [57, 58].

Another type of the efficiency that has to be discussed is area/land use efficiency. One has to treat land as non-renewable and strongly restricted resource, which should be used with a high efficiency, measured, i.e., as the yield rates per area of agricultural land. Another option to increase land use efficiencies from a wider perspective would be to establish plantations of, e.g., short rotation coppice or miscanthus on degraded/abandoned lands. Thus, the area devoted to the crop production is not diminished (reduction of competing use with the food), and simultaneously the overall land use efficiency is increased. In some cases, the land use efficiency strongly correlates to the water-use efficiency [59]. It is, for example, very difficult to improve land use efficiency in the arid and semi-arid regions in the Mediterranean countries, where the water resources are fully exploited and in some cases, even overexploited. Therefore, increasing, e.g., crop yields in these countries is impossible without implementation of the sound water management and irrigation programs.

To increase the land efficiency on existing agricultural areas, a broad variety of different measures may be used, including better agricultural practices, use of fertilizers, irrigation, etc. An interesting possibility of increasing the land efficiency is to use crop and plant residues, not utilized for other purposes. The obstacles with respect to land efficiency, however, may impede in some cases the efforts of efficiency increase in this area.

The next type of the efficiency to be taken into consideration in energetic use of the biomass relates to the materials use and the energy conversion efficiencies [60]. In general, the overall efficiency of the conversion (for instance, in the corn-based ethanol industry or in the area of lumber recovery in the wood industry) has increased in the past 20 years significantly [61]. The question appears, however, how to account the efficiency increase and – specifically in the case of the greenhouse gas emissions – how to decide, whether the efficiencies are high enough or not?

In the other words, what kind of reference systems should be used for the comparison of various existing options?

The most widely used tool for such comparisons between various conversion pathways and options is the Life Cycle Assessment (LCA). The LCA is known since the end of the 1960s; however, it is still considered to be relatively young and immature. As a consequence, there is no widely accepted methodology of conducting LCAs. Thus, the results of the LCA analysis for one product or service may differ according to the method chosen or assumptions made [62].

Another problem with setting the efficiency requirements is the relation between given conversion pathway and the reference or baseline scenario. The choice of the various baseline scenarios may have impact on the calculated GHG saving in the same way as the choice of the LCA method and the respective assumptions. Furthermore, the following assumptions may alter the final results:

- Inclusion or exclusion of the ILUC
- Choice of the historical data about (e.g., deforestation rates vs. biofuel production)
- Choice of the mathematical models
- Choice of the Life Cycle Impact Assessment methods and the modeling factors
- Origin of the biofuel and the production conditions
- The biofuel production technology
- End-use conversion efficiencies

The increasing efficiency is only one factor contributing to the successful and sustainable use of biomass. Another prerequisite of such use relates to the initial availability of the material for bioenergy production, which can be described with the term biomass potential (see below).

Sustainability

In the environmental discussion, the term “sustainable biomass potential” usually refers to the specified amount of raw materials, which may be used for bioenergy provision with simultaneous fulfillment of sustainability requirements. From a technical point of view, biomass potential is defined as the ability to obtain certain amount of the biomass/bioenergy from a given area in

a given time period. Usually it is distinguished between the theoretical potential (the total amount of energy that may be created in a given time period by using physically available biomass), the technical potential (part of the theoretical potential of the bioenergy that may be generated taking into consideration technical restrictions), the economic potential (part of the technical potential, amount of bioenergy that may be generated taking into consideration economic restrictions), and the available potential (the bioenergy that may be created in reality, after taking nontechnical and noneconomic constraints into consideration (like the emotional fear from new technologies, emotional barriers to use biomass, etc.) (Adapted from [4]).

Additionally there are also many other approaches toward depicting the possible potentials. For instance, a differentiation can be made according to the availability of biomass (based on the function and position of the material in the entire system) between:

- Area potential (the amount of the material on the given area of land)
- Material potential (amount of material that may be gained from the given area using the available technology)
- Fuel/energy carrier potential (amount of the combustible material that can be made from the raw material)
- Bioenergy potential (amount of the bioenergy that may be created after passing all different conversion routes)

Another aspect that has to be mentioned is the competition between various purposes, for which biomass may be used. This problem may be denoted as the “4F” dilemma. Namely, one has to ask a question: Which need(s) of the mankind should be satisfied first from the available biomass potentials: food, feed, fiber, or fuels? Decision makers and public attention focus currently mostly on the rising food prices as a (supposed) consequence of the growing demand of biomass used for biofuels. However, the system of the interrelationships between those four main purposes seems to be much more complicated and difficult to investigate. Therefore, a system of the different integrated models for assessing and evaluating sustainable biomass potentials should be created.

Sustainable use of biomass demands a clear view of the future biomass potential considering all the relevant sustainability aspects. This includes detailed regional specific information about soil and climate and assumption concerning the expected demand on biomass for food, feed, and materials (fibers).

There are no accepted rules yet to calculate sustainable potentials [63]. Therefore, in the following section, an overview on the debate on biomass potential assessment is given, which already includes sustainability aspects. Simultaneously, the open points of the discussion are described.

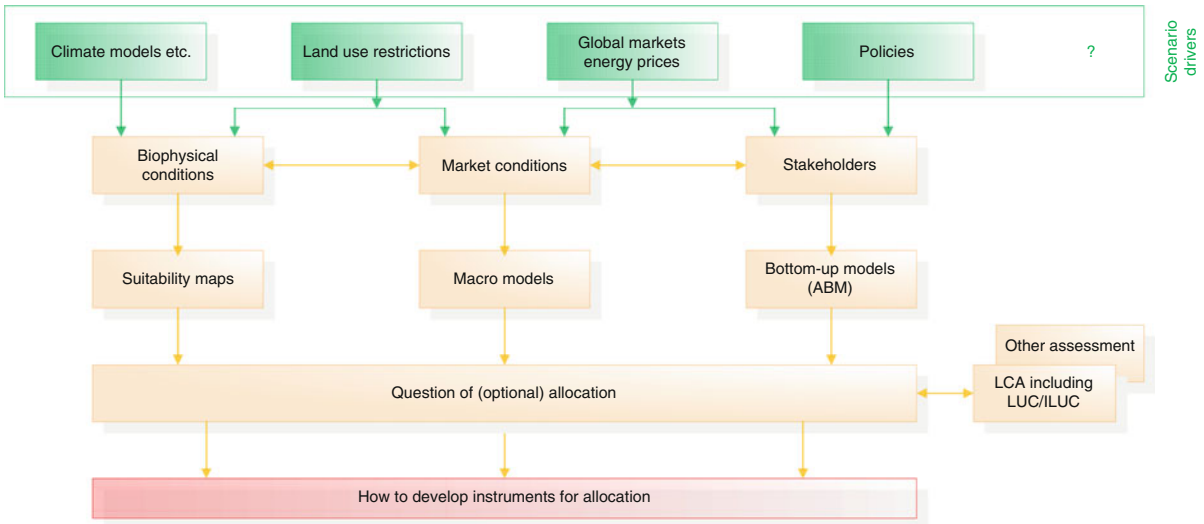
Since sustainability relates to many fields of the management and research, an integrated approach seems to be appropriate and necessary to obtain a comprehensive evaluation of the existing potentials. An example of such an integrated model for the biomass potential calculation is shown in Fig. 6. The areas covered by such models range from physics and chemistry (air pollution and climate change), biology and agriculture (land use and its restrictions as well as biophysical conditions), economy (costs and prices), and environmental sciences (Life Cycle Assessment, LCA). LCA studies are currently developing approaches to incorporate indirect land use changes in the results; however, so far there is no widely accepted and applied methodology which might be universally used. The

previously mentioned method applied by EPA in the evaluation of the GHG balances of the biofuels may be seen as the first forerunner of such an integrated modeling assessment. However, the models and the data used have still a great potential for improvement.

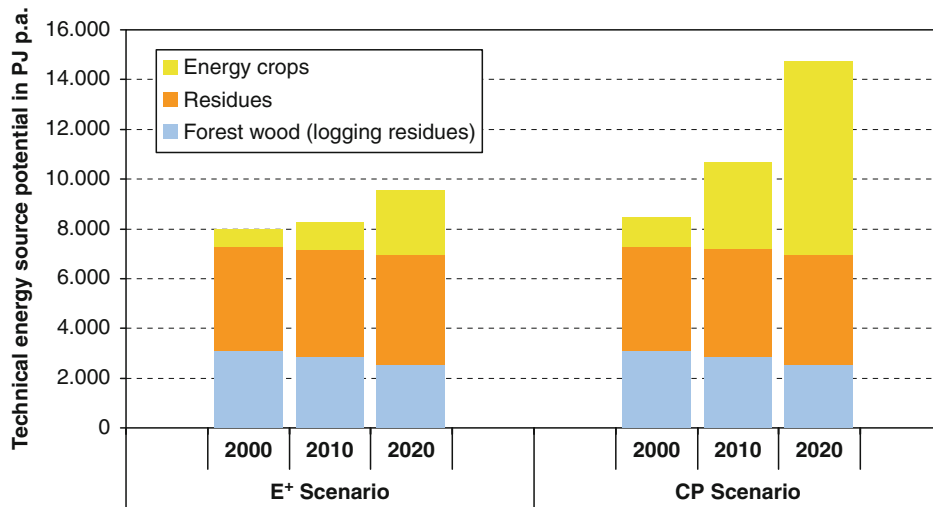
Factors Influencing the Biomass Potential

Even if a general approach for sustainable potentials is not available yet, the main influencing factors for the future biomass availability can be described. Therefore, in general, the technical biomass potential is analyzed as a realistic maximum. While the technical biomass potential from residues and wastes does mainly depend on human activities and the demographic development, the technical biomass potential from energy crops is linked to available arable land for energy crop cultivation which is influenced by a multitude of different drivers such as policy scenarios (Fig. 7).

The land availability for energy crop production depends on the overall amount of available agricultural land and the demand of land for food and fodder production. But there are various drivers influencing the present and future food and feedstock demand. Their magnitude depends on the climate zone, the soil quality, and specific local conditions. However, the main factors are universally valid in a global context. The following influencing factors may be



Biomass Provision and Use, Sustainability Aspects. Figure 6
Integrated potential assessment of the energy crops



Biomass Provision and Use, Sustainability Aspects. Figure 7

Current and expected technical biomass potentials. Example: European Union considering two different scenarios for the development of environmental standards for the agricultural production. E+: Environmental+scenario, CP: current policy scenario [64]

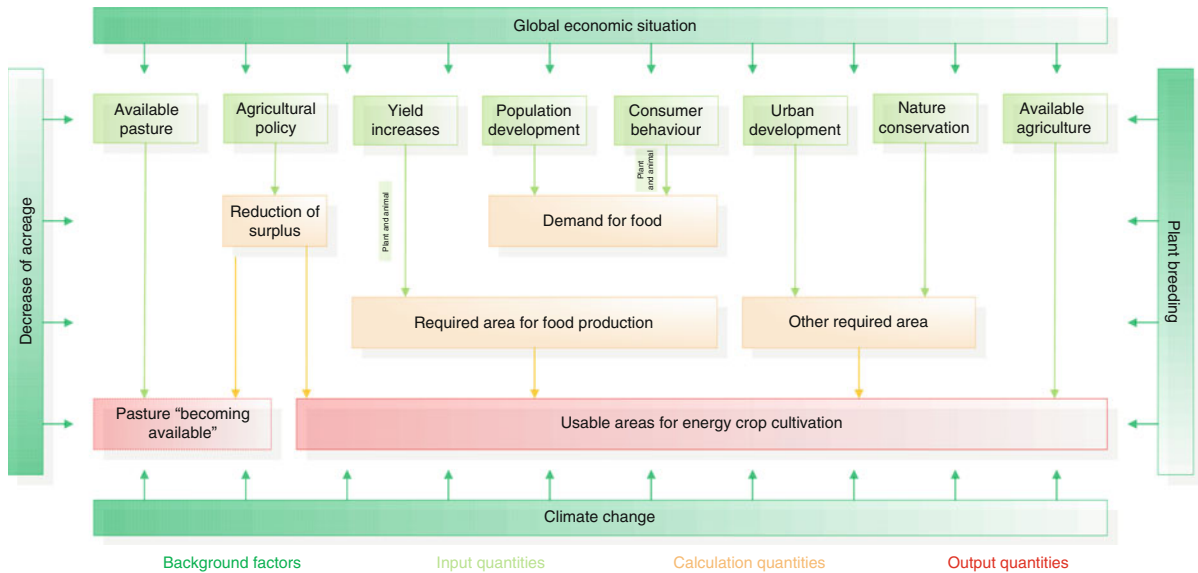
identified as those playing a crucial role on the world-wide scale [65]:

1. Development of the global population
2. Per capita consumption of food (global per capita consumption of food changes slowly but increasingly; the production of meat needs at least six times the acreage needed for the production of plant products)
3. Increase of harvests by increase of specific yields due to progress in plant breeding
4. Increase of yields by improving the state of the art (real situation in agriculture; i.e., assimilation of production systems particularly in Africa and Asia)
5. Climate change influence the availability of acreage and the development of yields
6. Loss of agricultural acreage by soil degradation (erosion, salinization) and additional need of areas for non-agricultural purposes (infrastructure, restrictions of use, etc.)
7. Competing needs for nature conservation
8. Acreage for flood protection
9. Extensification toward environmental protection
10. Use of resources as raw material in industry
11. Use of resources for attractive non-subsidized exports

Out of these factors, the most important ones are the development of the global population, the future per capita food consumption – both driven by the development of the worldwide economic growth – and the development of the specific yields for food, fodder, and biomass production. Climate change and its impact on the agriculture production will also be an important factor which, however, is very difficult to quantify [66].

Figure 8 shows the main drivers and connections between the different levels of the biomass supply system. According to this, various different factors need to be considered by potential estimates. The assessment of future biomass potentials has to include a range of uncertainties and thus, represents a very complex question.

The previously mentioned influencing factors may have a positive and negative impact on the areas available for biomass production and the biomass potential. The most sensitive drivers are the demand for food (potential reducing factor) and the increase in agricultural yields (potential increasing factor). One has to take into consideration, however, that the potentials and distributions vary largely according to the local conditions. Therefore, information of the biomass potential is necessary on the regional and country-related scale.



Biomass Provision and Use, Sustainability Aspects. Figure 8

Interrelationships and drivers of the biomass potential for energy crops (Adapted from [34])

Biomass Provision and Use, Sustainability Aspects. Table 5 Potential of agricultural land for energy crops in 2002–2005, in [10^3 ha]

Country	Fallow land	Surplus area from the production of			Sum
		Crops	Milk	Beef	
EU-27	14,145	9,390	4,919	2,140	30,595
Europe others	88,975	5,141	1,837	351	96,336
Europe total	1,03,121	14,531	6,756	2,491	1,26,932
North America	93,373	31,182	−400	373	1,26,123
Central America	15,279	1,241	−4,148	−2,322	17,468
South America	19,100	16,102	5,734	25,904	71,140
America total	1,27,753	49,985	7,604	29,296	2,14,732
Australia	24,909	12,268	65,658	89,925	1,92,760
Oceania	3,219	138	8,197	1,628	13,182
Asia	47,595	13,832	41	675	62,188
Africa	43,337	352	270	65	45,451
Sum (133 countries)	3,49,933	91,105	88,527	1,24,081	6,55,244

Table 5 presents the overview of the available agricultural land for the purposes of the energy crop production (i.e., historical data from 2002 to 2005). As it can be seen, the highest area potential occurs in Australia, Europe, and North America. Most of the land

available for energy crop production might be obtained from fallow land, followed by surplus area coming from the production of the beef, other crops, and milk. Nonetheless, in some regions, negative values occur, underlining the missing production capacities and/or

non-advantageous country characteristics. Another surprising fact is the low land availability in Africa and Asia, in relation to the total area of these continents.

The general characteristics of the key regions of the world may be described as follows:

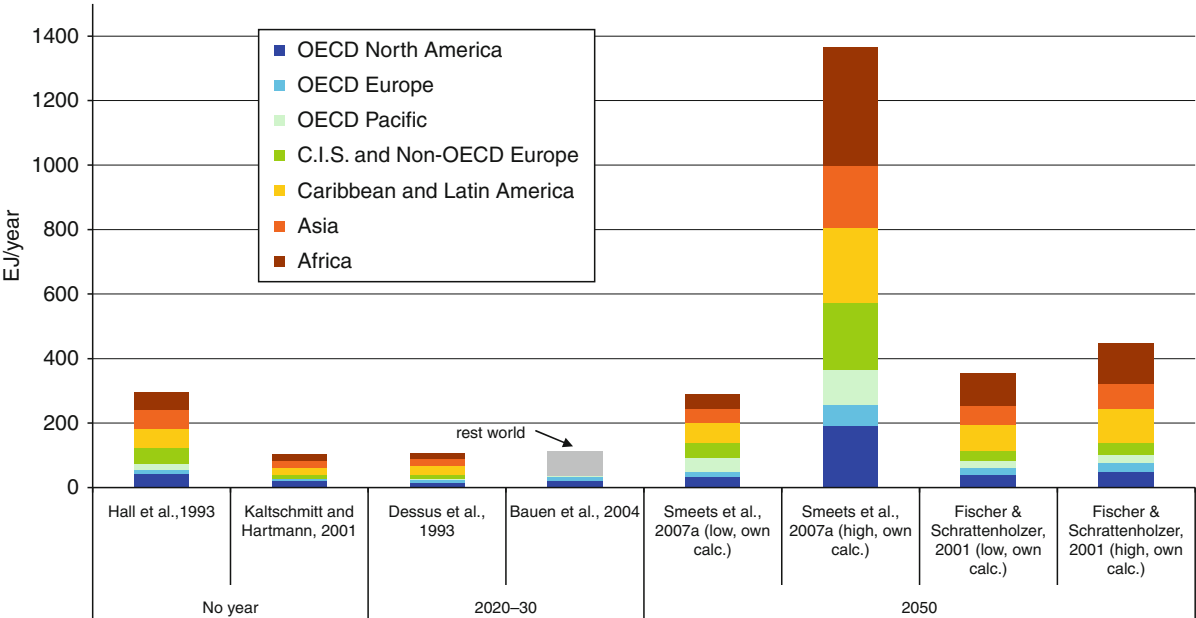
- Europe: relatively large area available for the biomass production; high productivity and efficiency of the production does not leave much space for surplus areas that could be used for the biomass production, especially in so-called old EU member states.
- Russia and the Ukraine: very large area (alone in Russia approximately 216 mn ha of the total agricultural land) available mainly in the form of the fallow land; the current productivity and production efficiency is very low, but may slowly increase in the future; in the middle term, it is estimated that both countries will increase their area potential for bioenergy sources.
- North America: large agricultural area, high yields per hectare, importance of the utilization of the genetically modified organisms (e.g., maize) may be observed; very high area potential.
- Latin America: the growth of agriculturally utilized areas may be observed; Brazil is especially important from the point of view of sustainability, since it is a big ethanol producer.
- Asia: increasing yields per hectare combined with a small area of available land per capita allow to maintain currently the self-provision with food; very small area available for the production of the energy plants; sustainability problems in Malaysia/Indonesia related to the conversion of the carbon-rich soils into palm plantations.
- Australia: one of the highest surplus of the grain exports in the world and approximately 440 mn ha of agricultural land; however, the area potential is expected to decrease due to the growth in population, reduction in yields, and diminishing agricultural land.
- Africa: currently relatively small area potential due to the non-advantageous climate conditions; however, the biomass potential occurring in the other fields of biomass provision.

For the assessment of the sustainable biomass potential, the following areas of the biomass

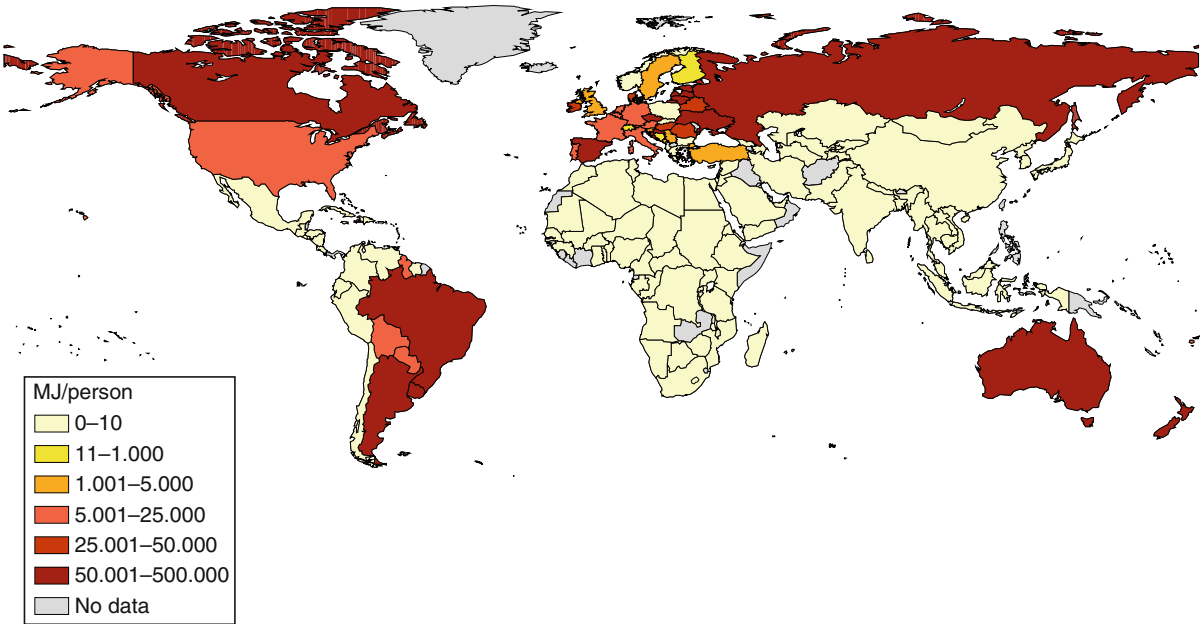
provision pathways, where social, environmental, and economic requirements could be met, are taken into consideration:

- The cultivation of the perennial plants on marginal, idle, or degraded lands abandoned from the agricultural use; in such way, the several negative aspects related to the biomass use are being minimized, namely competition with food crops, direct and indirect land use changes related to the biofuels expansion, which is inevitable associated with the creation of the long-term land clearing-associated carbon debts and biodiversity losses.
- Use of the abandoned crop residues, not utilized for the food production or other purpose. Here, the crucial aspect would be related to the maintenance of the soil fertility (known as humus balance); however, some amounts of the residues might be used, e.g., for energy purpose.
- The sustainable uses of the forest residues, including wood branches, sawmill operation rests, etc.
- Cultivation of the double crops and mixed cropping systems. In the first case, the crops for the bioenergy purposes might be grown between the summer periods, when the traditional crops for the food purposes are cultivated. In the second case, systems which may grow simultaneously for food and energy purposes are summarized.
- Conversion of solid waste streams, rich in organic matter such as municipal and industrial wastes, into, e.g., liquid fuels. Sometimes the declining potential of this source of bioenergy is mentioned due to the minimizing the waste losses in industry and improving the production efficiencies [41, 67, 68].

Concerning these factors, the future potentials for residues are projected to be in a smaller range than the potential for energy crops. Because of the uncertainties mentioned above, energy crop potentials are often assessed with scenario approaches. As a result, various information on the current and future biomass potentials are obtained. Figure 9 presents a comparison of some studies focusing on the current and future potential. As one can see, the difference between the estimation varies from approximately 100 EJ per year up to almost 1,400 EJ per year in 2050.



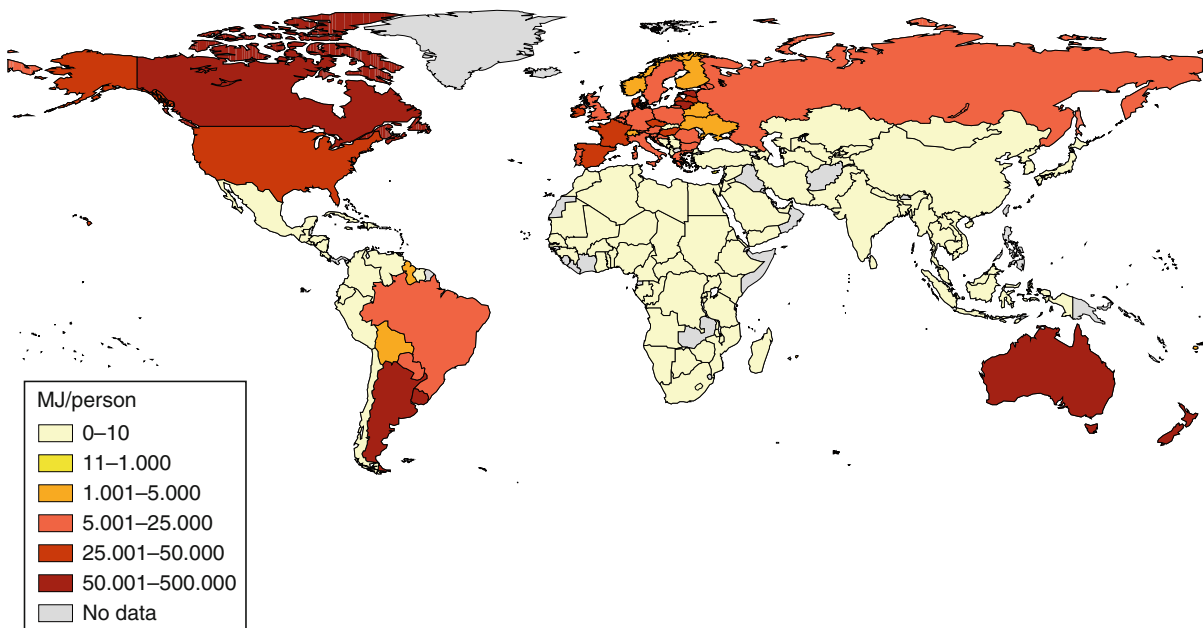
Biomass Provision and Use, Sustainability Aspects. Figure 9
Fuel potential for the various regions of the World (Data of [66, 69–85])



Biomass Provision and Use, Sustainability Aspects. Figure 10
Biomass potential in MJ/person in “business as usual” scenario for the year 2020

The question appears about the role and influence of sustainability standards on the availability of biomass for energy production. As it appears, obeying the “strong” sustainability rules does not automatically

result in the reduction of the energy crop potentials. Figures 10 and 11 compare the energy crop potential for a “business as usual” scenario and an “environment and health” scenario, which predict stronger



Biomass Provision and Use, Sustainability Aspects. Figure 11

Biomass potential in MJ/person in “environment and health” scenario (ecological approach in agriculture and change in eating habit) for the year 2020

environmental standards (no additional land use change), but also a adoption of the food-consumption-pattern (reduction of meat consumption to a more “healthy” level):

- In the “Business as usual scenario” it was assumed that the legal, economic, and environmental conditions in the future will be exactly the same as today. That means that some negative processes are continuously taking place (e.g., agricultural area degradation, forest clearing, loss of land area for the industrial and residential purposes). Although the ecological agriculture is growing and the fertilizer input is being minimized according to the regulatory trends, the scenario assumes that the conventional production techniques still prevail.
- The environment and health scenario is assuming both: application of the ecological and sustainable land management practices, as well as change in eating habits of the specific countries according to the recommendations of the World Health Organization.

As a result of the “business as usual” scenario calculations, one may see that the global biomass

potentials are the highest on the northern hemisphere, in the bigger part of the South America and in Australia. In Africa, Asia, and some countries of the Central and South Africa, the calculated potential is very low (approximately 0 to 1,000 MJ/person, Fig. 10). This is due to the previously mentioned conditions, such as high population number or non-advantageous climatic conditions.

The results of the “environment and health” scenario are in the same range as the “business as usual” scenario. As a result, one may observe an increase in the biomass potentials in most of the industrialized countries and in Russia.

The use of a degraded land, which is also discussed as a relevant biomass potential was not considered in both of the scenarios. Taking those lands for biomass production includes especially social risks, because they are primarily located in developing countries.

Summary

The increasing use of biomass as a consequence of the political decision concerning the minimization of GHG emissions has revealed that the provision and use of

biomass may also have some negative impacts on the environmental, social, and economic spheres of life. As a consequence, various actors and decision makers have decided to employ the concept of sustainability to avoid or minimize potentially negative influence of the biomass use. This entry has discussed the state-of-the art, ongoing developments and the future perspectives in the following areas of the biomass sustainability:

- Sustainability requirements
- Crucial factors to be taken into consideration by sustainability
- Requirements along the biomass process chain
- Life-cycle analyses and the indirect influence of the policies and decision making
- Creation of the standards, certification schemes, and binding laws
- Demands and methodologies for the assessment of sustainable biomass potentials

As it appears, supplying and using biomass in a sustainable manner requires taking into consideration and simultaneously modeling very complex, multi-level interconnected systems. First steps have been done in the last few year, but additional effort has to be taken to include also land use, social aspects, and environmental demands.

Future Directions

The approach toward sustainability depends on the type of stakeholder and its point of view, interests, which subsequently determine different strategies and specific measures. There are four main levels, at which sustainability issues may be developed and proliferated, namely:

- International (e.g., European Union), national, and regional authorities, issuing mandatory laws and standards
- Complementary measures issued on the international, national, and regional levels
- Commercial implementation of sustainability initiatives
- Activities of the non-governmental organizations (NGOs) [86]

The importance of a sustainability approach becomes more important, when creating the binding laws and standards for the biomass market (e.g., biofuel

standards). Here, the contradictory interests of biofuel producers (which would like to have their fuel to be recognized as environmentally friendly and being produced in a sustainable manner) and various NGOs and research institutions (which underline, e.g., indirect land use changes) become obvious.

Since the discussion about sustainability of biomass started in the last decade, there are no widely accepted definitions of what sustainability in the context of biomass should mean. Depending on the type of player (international organizations, governments, NGOs, industrial associations, etc.), sustainability is defined in a wider or less detailed perspective. However, it is well visible that the future developments of sustainability requirements will focus on the following issues:

- Protection of highly biodiverse ecosystems and of carbon stocks
- Maintaining carbon balance of the soils
- Emissions from land use, land change, and forestry (LULUCF)
- Reductions of the greenhouse gas emissions in comparison to fossil fuels application
- Reducing energy consumptions and increasing the efficiency [30]
- Not causing any shifts in the GHG emissions (indirect land use changes)

Those targets cannot be successfully achieved within the bioenergy field alone, but demand more complex and comprehensive action and additional efforts in agriculture, energy supply systems, and an international debate on land use in general as well.

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Biomass Pyrolysis

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Article Outline

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Glossary

Fast pyrolysis Heat up of the sample within 1–2 s and the condensation of products within seconds.

Intermediate pyrolysis Heat up of the sample within minutes (1–10) and the rapid condensation of products within seconds.

Pyrolysis Pyrolysis is the thermochemical conversion of feed material under the absence of oxygen; usually products of pyrolysis are char, liquid, and gas.

Slow pyrolysis Heat up of the sample within hours or days.

Thermochemical conversion Treatment of material at elevated temperature and which is causing chemical conversion reactions like cracking, radical reactions, decarboxylation, and so on.

Definition and Importance of the Subject

Pyrolysis is the oxygen free thermochemical conversion of materials. Pyrolysis turns a feed like biomass into three major products: gases, liquids, and char. The char contains the ash and is often called biochar. Pyrolysis is able to condition or liquefy biomass. For most of the processes and feedstock materials the liquid contains of two phases, a water rich and organic rich fraction.

By means of pyrolysis, several types of biomass feedstock can be made suitable for gasification or combustion. A solid feed is turned into gas and liquid, or a slurry, which is a mixture of liquid and char. For combustion purpose, the char is very suitable which is in most cases brittle and possible to use in a coal-fired power plant or a biomass power plant.

Introduction

Pyrolysis in general is the thermochemical conversion of feed material under the absence of oxygen. Pyrolysis reactors exist in various designs and for various pyrolysis conditions as fast, intermediate, or slow. Traditionally, the slow pyrolysis is known, for example, for charcoal production. This chapter is dealing with

the more advanced pyrolysis types for fast and intermediate pyrolysis. It will give an overview of reactors and technical applications and the related state of the art. The final sections will deal with the numerical simulation of the processes as well as the post treatment of pyrolysis chars to activated carbon.

Pyrolysis of biomass is of a different kind in terms of feedstock, applied reactors, as well as applied type of pyrolysis – fast, intermediate, or slow pyrolysis. The classical approach on slow pyrolysis leads to charcoal or even finally to activated carbon, starting from wood. The opposite of this is fast pyrolysis of wood in creating a maximum of liquid phase for this specific feedstock and usually tar containing chars.

More difficult as the pyrolysis of wood is the pyrolysis of nonwoody biomass and the application of its products. A new type of pyrolysis is the intermediate pyrolysis. In between the reaction conditions of slow and fast pyrolysis, it offers much different product qualities of liquids, gases, and of the biochars, the residue from pyrolysis. The distribution of product phases is affected as well as the composition of the liquid phase. It is of importance that the reaction conditions for intermediate pyrolysis offer a wide range of variation for the process optimization.

Kinetic Parameters and Degradation Mechanisms

Biomass essentially can be converted to energy and clean fuels via thermochemical processes. In every thermochemical process, pyrolytic degradation plays a significant role. Attempts were made to correlate the characteristics of biomass pyrolysis with those of its components using overall kinetic models [1–3]. The agreement of these models was only at a specific heating rate, and the reason could be related to influence of heating rate on char formation. Understanding the physical dynamics (weight loss behavior, morphological and structural changes with respect to time and different heating rates) may lead to improved methods of conversion. Among various approaches to obtain the kinetics, the simplest ones are to use empirical and employ global kinetics, by using the Arrhenius expression and to correlate the rates of mass loss with temperature [4].

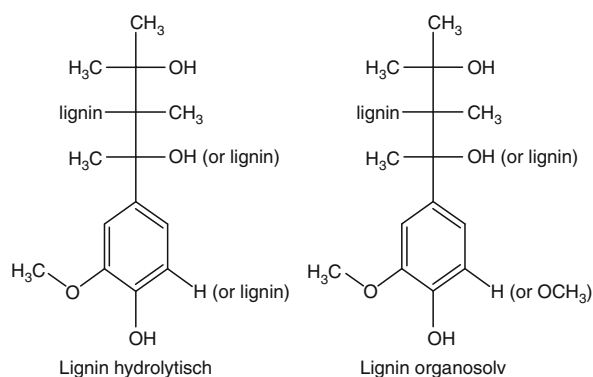
Increasing applications of lignocellulosic materials for energy production have increased the need to know

its detailed reaction mechanisms and thermal behavior. From energy economic point of view for control over product generation and their composition, the thermal behavior studies of lignin is very crucial. Lignin in general is more thermally stable, produces more char and higher fraction of aromatics in the liquid product compared to cellulose and hemicellulose under similar conditions. In this study, the TG-MS techniques are used to evaluate the thermal characteristics and formal kinetic parameters for pyrolysis of different kinds of lignin. A mathematical model for basic studies under integration with the experimental data is realized.

Experiments were carried out using different kinds of lignin. Tests were carried out with technical lignins, hydrolytic and organosolv. The hydrolytic lignin is typically a G type lignin. Organosolv lignin was of the H type lignins. The structures of these lignins are shown in Fig. 1.

The branched macromolecular structure of hydrolytic lignin contains primary and secondary aliphatic as well as phenolic OH groups. The methoxyl content is in the range of 9–11%. It is linked to neighboring phenyl propane repeat units via C–C and C–O–C bonds. C=O groups are also present, and the phenolic OH groups were predominant over the aliphatic OH groups compared to the presence of the methyl groups. The hydrolytic lignin has an ash content of 2–3% with an average molecular weight of $19,300 \text{ gM}^{-1}$.

Organosolv lignin contains primary and secondary aliphatic as well as phenolic OH groups. It has an elemental composition of Carbon 66.5%, Hydrogen 6.1%, OCH_3 18.9%, sugars <0.5%, and ash <1%.



Biomass Pyrolysis. Figure 1

Structure of hydrolytic and organosolv lignin

This type of lignin also has C=O groups, and the amounts of the phenolic and aliphatic OH groups are almost equal with an average molecular weight of $3,500 \text{ gM}^{-1}$.

In order to understand the degradation mechanisms of lignin, it is important to understand the structure of lignin; in the sense, what kind of linkages and reactive groups are present. The lignin structure constitutes peripheral groups, aromatic nuclei, labile bridges, and char links. The chemical structure (CS) comprises:

- The nature of the repeating units
- The nature of end groups
- The composition of possible branches and cross-links
- The nature of defects in the structural sequence

The chemical reactions can occur at the principal polymer backbone and also at the sites of repeated units. The propagation of the chemical reactions can affect both the molecular weight distribution and the chemical structure of the polymer [5].

The releasing of gas and tar components in the vapor phase with the simultaneous carbonaceous residue formation is determined by an enormous number of chemical reactions. These involve different precursors and intermediates in the condensed phase. The evolution of a specific product is strongly affected by the structures of the corresponding precursors. Tar is generally defined as the volatiles that condense at room temperature. Many tar components are recognized to be directly derived from the starting repeated unit of a specific macromolecular constituent of biomass. Volatiles are made of noncondensable gases with high heating value, light oils suitable as fuels and feed stocks, and high boiling tars for subsequent refining.

In lignin, the aromatic groups can be considered as refractory nuclei, which remain intact both in tar and char formation. Chemical constitution and reactivity of the linkages between the monomers has strong affects on the shortening process of the polymer chain and on the tar and char formation. The description of reacting phase is completed by overall characterization of the peripheral groups. They promote bimolecular reactions and affect the permanent gas formation in pyrolysis process. The diverse variety of lignin is rendered with four structural components: non-reacting carbon (aromatic nuclei), labile bridges, char links, and

peripheral groups. Repeated units are interconnected by labile bridges or char links. Labile bridges represent aliphatic, alicyclic, and heteroatomic functionalities, not distinct chemical bonds. Peripheral groups are the remains of broken bridges on fragments ends that have the same composition. Labile bridges that decompose into char links during devolatilization leave a fraction of their oxygen in the char link. The residual oxygen is released as CO at high temperature.

The numerical kinetic analysis extends the interpretability of temperature-programmed conversion of biomasses, and it is potentially useful for the elucidation of fundamental reaction mechanistic information. The TG analysis represents the starting base for the computation of the main kinetic parameters. The numerical results in comparison with the experimental results are shown in the Fig. 2.

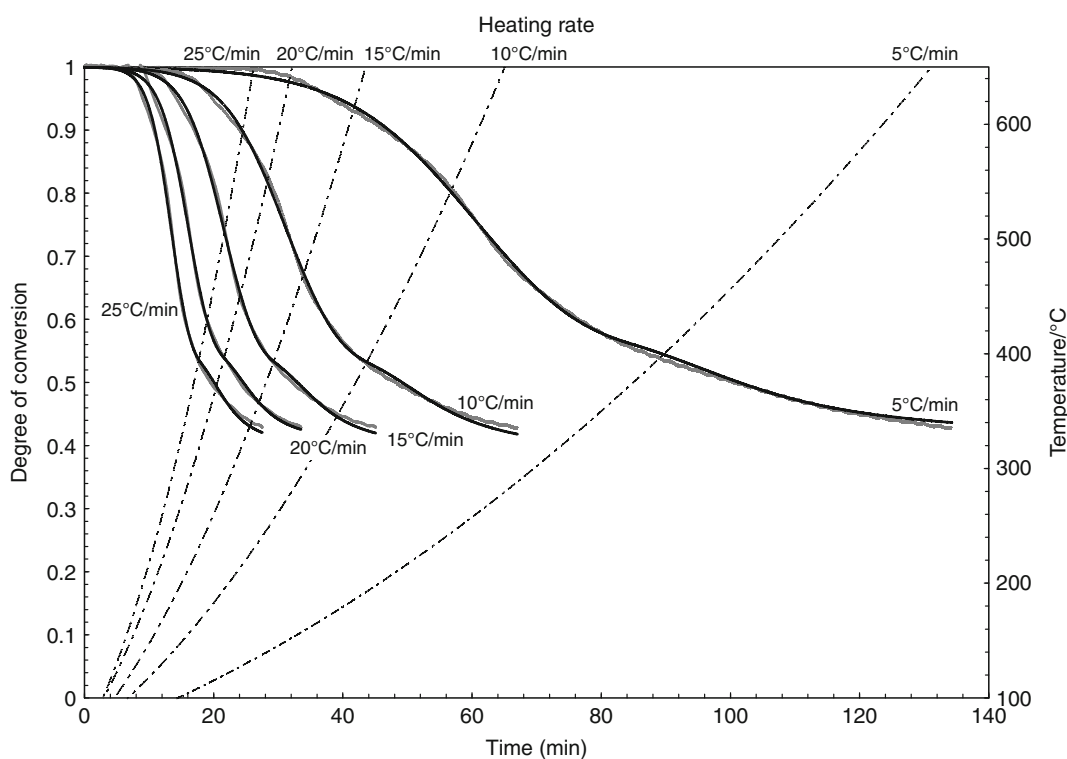
The increasing in complexity of the model allows monitoring the time/temperature evolution of the main families of components. The model is able to reproduce the main trend with the increasing of

the overall heating rates as established by the mass spectrometric investigations. As shown in Fig. 3, the developed model is also able to predict the lignin thermal behavior for high heating rates giving useful information for operative conditions, which are not easily achieved, in the lab-scale level. The total amount of char, tar, and permanent gas at different pyrolysis temperatures and different overall heating rates, which are not easy to realize in lab scale, are done by numerical methods.

Fast Pyrolysis

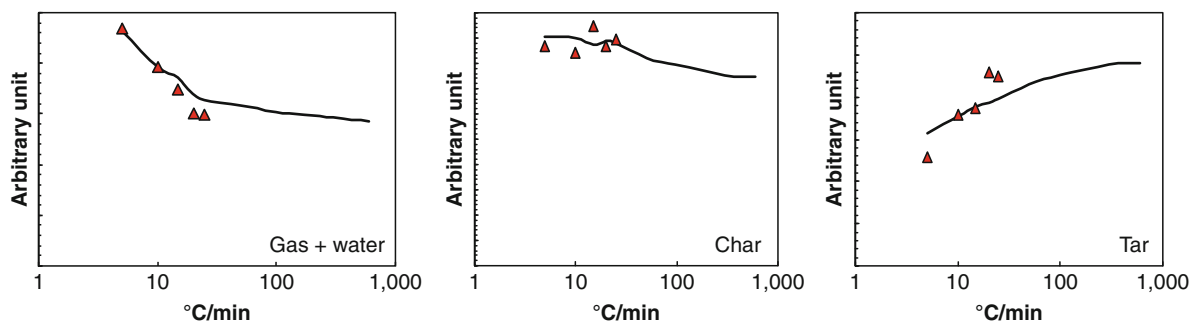
Pyrolysis is thermal decomposition occurring in the absence of oxygen. During pyrolysis, the feed is cracked and not oxidized or partially oxidized like in gasification or combustion. During pyrolysis, always a set of products is resulting: charcoal, liquids, and gas.

By means of fast pyrolysis, thermal energy is transferred within seconds into the organic material



Biomass Pyrolysis. Figure 2

Pyrolysis of hydrolytic lignin at different heating rates model development (*gray*) and experiments (*black*)



Biomass Pyrolysis. Figure 3

Total yields of the main products families from pyrolysis of hydrolytic lignin at different heating rates and at a final temperature of 500°C. Comparison and predictions (marks = experimental data). The y axis stands for arbitrary yields given as a function of the heating rate used

and the resulting vapors are removed from the hot reaction zone within seconds. Both parts of the process usually have residence times of 0.5–2 s, and the character of the products is mainly defined by the high energy flow into the sample. Typical for fast pyrolysis is therefore a higher tar formation during pyrolysis. Especially during fast pyrolysis of nonwoody biomasses, the liquids are higher in viscosity and tar content compared to those from intermediate pyrolysis.

In terms of woody biomass, the fast pyrolysis is of interest for liquid production, as the liquid is received in very high quantity, up to 75% (compare Table 1).

Principles

Below the most important principles are summarized:

- Very high heating rates, up to 1,000°C/s
- Fine-grounded materials, particles of several millimeters down to several 10 µm
- Typical reaction temperatures from 400°C up to 550°C, higher or lower temperatures are given in literature
- Short vapor residence times of 1–2 s
- High cooling rates for the vapors to reduce thermal post decomposition

Process Technology




Bubbling Fluid Bed Reactor The bubbling fluidized bed is a simple and well-understood technology (Fig. 4). The advantages are good temperature control and efficient heat transfer due to high particle density.

Pilot (approx. 250 kg/h) and technical scale (up to 200 t/day) units are available (e.g., [1–3]).

Circulating Fluid Bed Reactor Circulating fluid bed reactors are more complex than bubbling fluid bed reactors (Fig. 5). Compared to bubbling fluid bed reactors, the residence time of the char is almost the same as the residence time of the gases and vapors. Due to higher gas velocity, the char is transported rapidly through the reactor which usually leads to higher char contents in the pyrolysis oil. A counter measure is the involvement of filters to keep back the particles. The circulating fluid bed is very popular especially because of its high throughput. The heat for the process is realized by burning the char while heating the sand in a separate reactor unit and recirculation of the hot sand into the circulating fluid bed (for examples of this technology see [5–7]).

Ablative Pyrolysis Reactor At the ablative pyrolysis, the heat transfer is optimized by having a huge heat transfer surface and a small sample surface pressed against it (Fig. 6). The biomass, usually wood, is pressed mechanically against the hot surface and the hot surface is passing by. The reaction rates are not limited by heat transfer. Therefore, larger wood particles can be used or a solid compressed stick of wood chips is pressed against a hot rotating plate (hydraulically fed wood rods) [8, 9]. Within an alternative approach, fine particles are pressed with supersonic velocities (high tangential pressure) against the inside of a cylindrical reactor [10]. Within another

Biomass Pyrolysis. Table 1 Pyrolysis of wood under fast and slow pyrolysis conditions

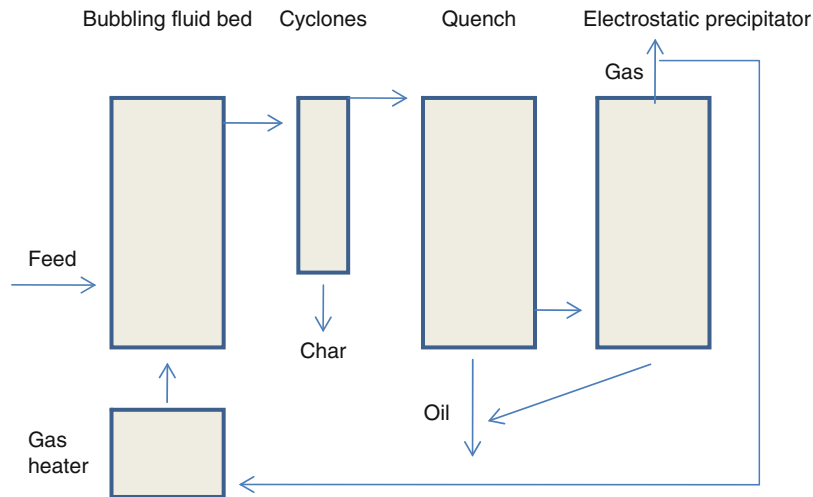
	Fast pyrolysis 500°C	Slow pyrolysis 420°C	Slow pyrolysis 500°C	Slow pyrolysis 600°C
Total liquid, wt% on dry feed	75	51.9	52.8	51.9 
Char yield, wt% on dry feed	8.5	33.6	31.9	32 
Gas yield, wt% on dry feed	10.9	13.4	11.3	11.4
Closure, wt% on dry feed	94.4	98.9	96	95.3
Heating rate (°C/min)	–	14.5	13.7	12.6
<i>(Slow pyrolysis liquid from dry ice and acetone condenser-water and light ends)</i>				
Water content (%)	20.8	45.9	48.2	43.8 
Char content (%)	0.04	0.02	0.03	0.03
Viscosity (cP)	53.8	1.4	1.1	1.8
PH	2.4	2.3	2.5	2.4
<i>Elemental analysis (%)</i>				
C	43.9	28.13	28	27.39
H	7.4	9.38	9.38	9.55
N	0.07	0.03	–	–
O by difference	48.6	62.5	62.7	63.1
HHV (wet) (MJ/kg)	14.4	6.8	6.4	7.1
<i>(Slow pyrolysis liquid from EP – heavy organic fraction)</i>				
Water content (%)	–	8.6	11.3	7.8
PH	–	2.8	2.6	2.6
<i>Elemental analysis (%)</i>				
C	–	54.8	53.75	55.30
H	–	7.14	7.41	7.23
N	–	0.10	0.13	0.16
O by difference	–	38	38.72	37.32
HHV (wet) (MJ/kg)	–	21.3	20.4	21.8

Source: Bridgwater et al. [32].

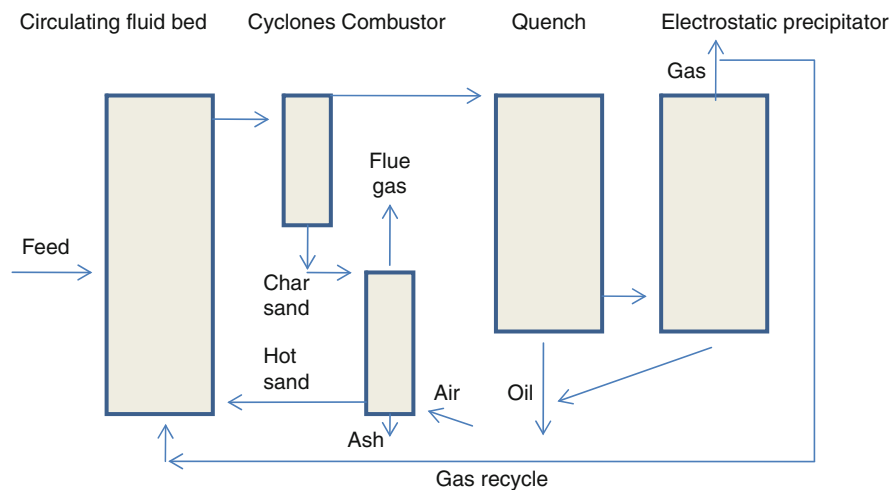
development pressure and motion is derived mechanically within a rotating blade reactor [11].

Twin Screw Reactor – Mechanical Fluidized Bed
Here, fast pyrolysis is accomplished in a twin screw mixer reactor heated by a solid heat carrier. Central

parts of the fast pyrolysis system are a reactor with twin screws rotating in the same direction, cleaning each other with intertwining flights and a heat carrier loop which can be designed in several ways [12]. The heat carrier can consist of sand or steel shot (Fig. 7).



Biomass Pyrolysis. Figure 4
Bubbling fluid bed reactor

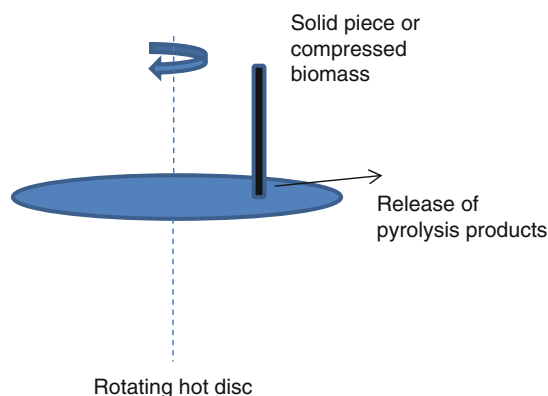


Biomass Pyrolysis. Figure 5
Circulating fluid bed reactor

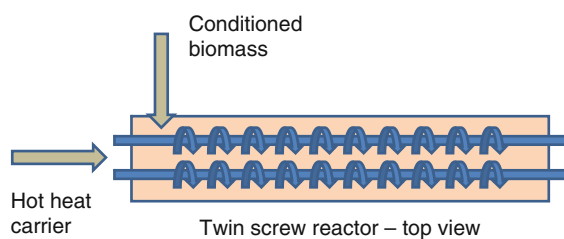
The abrasive character of rapid moved sand or steel shot results in high amounts of char dust and is usually making it difficult to separate the vapors from the char after pyrolysis. Measures like cyclones and hot gas filtration have to be taken to improve the quality of the pyrolysis liquid.

Rotating Cone The rotating cone reactor [13, 14] effectively operates as transported bed reactor. The transport is affected by centrifugal forces in a rotating

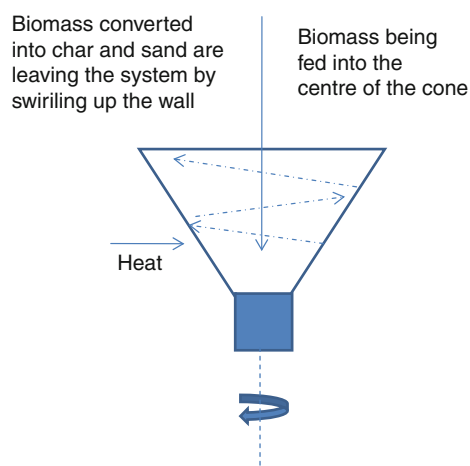
cone. The heat transfer is realized by hot sand, generated in a bubbling bed char combustor, where the remaining char from pyrolysis is oxidized to heat up the sand [10] (Fig. 8). The char application is integrated to heat the sand, and the rotating cone is improving the heat transfer, but is less abrasive than the twin screw system described in Sect. “[Twin Screw Reactor – Mechanical Fluidized Bed](#)”. Finally, the system has been applied successfully for the conversion of open fruit bunches from palm in Malaysia by [13].



Biomass Pyrolysis. Figure 6
Ablative pyrolysis reactor



Biomass Pyrolysis. Figure 7
Twin screw reactor



Biomass Pyrolysis. Figure 8
Rotating cone reactor

Intermediate Pyrolysis

Intermediate Pyrolysis differs from fast pyrolysis in terms of the heat transfer to the feed. The heating rates are much lower, in the range of 100–500°C/min. This leads to less tar formation during the pyrolysis process as more controlled chemical reactions are taking place instead of thermal cracking of the biopolymer. The vapor residence times are very much dependant on the reactor type, but can be like in case of fast pyrolysis as low as 2 s.

In terms of the pyrolysis of woody materials, intermediate pyrolysis is producing much lower liquid fractions, about 55% compared to 75%. Nevertheless, this is valid only for the pyrolysis of woody feeds and changes to a more equal scenario in case of other biogenic materials.

Principles

Below the most important principles are summarized:

- Moderate heating rates, up to 200–300°C/min
- Residence times of several minutes, up to 10 min
- Coarse, shredded, chopped, or fine-grounded materials can be used as single feed or in mixtures, particles of several centimeters down to dust can be used
- Water content of the feed up to 40 wt%
- Typical reaction temperatures from 400°C up to 550°C, lower temperatures down to 350°C are possible
- Short vapor residence times of 2–4 s
- High cooling rates for the vapors to reduce thermal post decomposition

Process Technology

Typically, two major types of rotary kilns are used for intermediate pyrolysis processes: internally or externally heated systems. For internal heated kilns, a heat exchanger based on steam or gas powered tubes or electrical heaters are used. For externally heated systems, there exist steam, gas (direct or indirect), or electrical-powered systems. The following examples show engineering solutions for processing of high volatile feeds or relevance in processing.

Conrad Process The Conrad recycling process uses a horizontal auger kiln reactor that applies heat to the

feedstock [15–17]. The control of the pyrolysis process is decided by temperature, and especially auger speed and temperature.

Double Rotary Kiln Pyrolysis The double rotary kiln pyrolysis is designed for mechanical coupling of a pyrolysis unit and a combustion unit. The coaxial system of two rotary kilns opens up the possibility to evaporate organics from the feed material in the inner kiln, while the carbonaceous residues are transported through the external kiln to a combustion zone. The process heat of combustion is used to heat the inner kiln while the ashes are leaving the system [18]. Both kilns can be equipped with lifters or spiral lifters.

Low-Temperature Carburization Process The low-temperature carburization process (LTC) meets the need for a process, which economically reduces petrochemical and hydrocarbon residues into recyclable products, feedstocks, or clean fuels. The indirectly fired rotary kiln system can be operated up to 850°C. The throughput varies in between 800 and 2,000 kg/h.

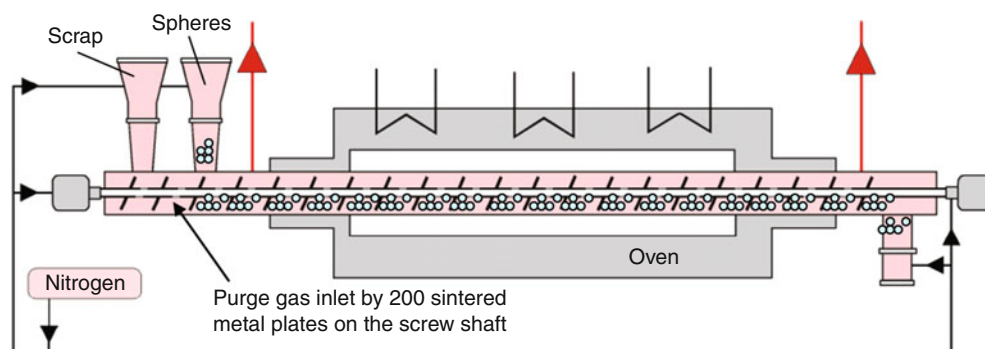
The LTC kiln sealing system allows operating the system under positive pressure, assuring no leakage of air which can produce an explosive mixture.

For cleaning the kiln wall from carbonaceous materials and feed, a cylindrical cleaning device has been developed lying on the bottom of the rotary kiln, equipped with high-temperature bearings effective even a temperature range up to 1,100°C, running up to 8,000 h/a without lubrication. The cylindrical unit is

mounted on the infeed side of the kiln and ends in the carburization zone of the kiln. A cone segment connects to the infeed zone.

Haloclean-Gas Tight Rotary Kiln Haloclean rotary kiln is especially designed for the pyrolysis of high amount of inert and/or thermosetting containing materials. The invention is based on the experience with a vertical reactor system for pyrolysis, the so-called Cycled-Spheres Reactor [19]. A system has been developed [20] improving the heat transfer to poorly heat transferring materials like plastics and biomass, ensuring that decomposition in laboratory scale can also be described with micro kinetic analysis [21]. The usage of a spheres-filled reaction vessel improves the heat conductivity by order of magnitude at least one [9]. The system used a screw cycling metal spheres. The idea of heat transferring metal spheres and a screw which not only transports spheres but also feed material was kept and transferred into an industrial-like reaction system, a rotary kiln [22]. To keep the performance in low rates of consecutive reactions of the pyrolysis gases as well as low residence times of the pyrolysis gases in the system at all, the hollow screw shaft has been equipped with 200 sintered metal plates. These plates are permanently cleaned by the material passing their surface, thus keeping the inner core of the screw clean from pyrolysis products, and they are introducing the purge gas directly where the pyrolysis products are evolved (Fig. 9).

By the screw the residence time control of the rotary kiln is completely different to existing kiln types. Feed and heat transferring spheres are transported in



Biomass Pyrolysis. Figure 9
The Halocean reactor

distinct volumes through the kiln. By using the screw in forward and backward movements, the residence time can be shifted to very long times, keeping the material permanently in motion and mixing. The system is indirect electrically heated by an outer oven and by the screw. Up to now the system is realized in pilot scale [23–25] and has been transferred to technical scale (20,000 t/a) in 2009 (see Annex 1 for an example).

The Pyroformer The Pyroformer [26] combines pyrolysis with enhanced char catalyzed reforming and is increasing the gas production. Higher gas productions rates are favorable especially if the pyrolysis is coupled to a gasification system. The reactor consists of two coaxial screw units (Fig. 10). The inner auger transports the biomass through the reactor and the outer screw transports the char back to the inlet zone, where the char is mixed together with the fresh biomass. The char is therefore heat carrier and reaction partner.

Slow Pyrolysis

Slow pyrolysis is the oldest way of treating biomass under oxygen free conditions and the most traditional. The production of barbecue charcoal is the best known example. Together with the production of charcoal, related products can be achieved like acetic acid or alcohols. Usually the pyrolysis vapors are used to deliver the heat for pyrolysis in a direct or indirect mode, which means either to heat the kiln from outside or to heat the biomass by getting it in contact with the combustion gases from pyrolysis gases. A third way is

to go for a partial oxidation, but this is outside the theme of pyrolysis.

Principles

The material used for this type of pyrolysis is shaped from briquet size to whole logs. Usually the feed material is traditionally wood, recent literature also shows cashew nut shells and palm [27–29].

The residence time of the solid phase is usually hours, up to weeks. For almost ash-free materials, the residue goes down to 15%, usually around 30% are found.

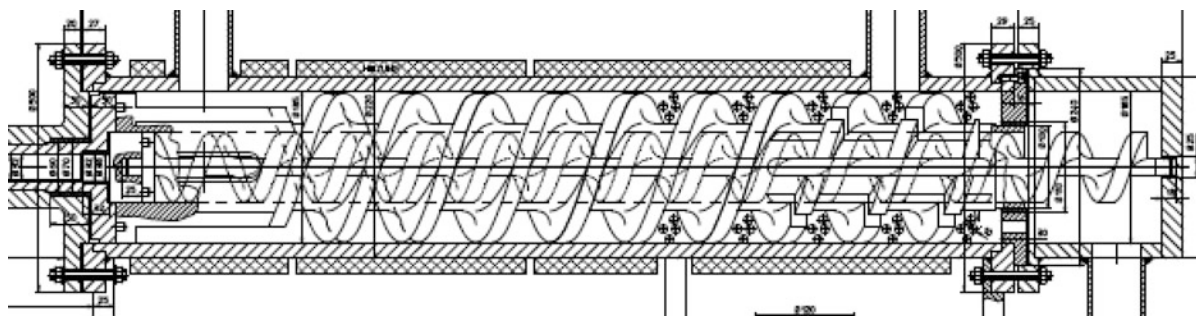
The heating rates are several degrees per minute.

A slow pyrolysis taking place within 1–2 h and at a heating rate of approximately 5 K/min will have a nearly even distribution between char, liquid, and gas.

Process Technology

A modern batch process with recirculation of the combustion gases is the Degussa process.

The process is based on a large retort with a capacity of 100 m³. The retort is fed by a belt conveyer from the top. After charging, hot gases are reaching the feed and over 16–20 h carbonization takes place. The pyrolysis gases are leaving the retort. The condensables are removed in a cooler and scrubber unit, noncondensables go to a heat exchanger, where the gas is heated by using the remaining pyrolysis gas fraction. The temperature for carbonization is about 450–550°C. The charcoal is discharged from the bottom and fall into air-tight bunkers for cooling (Fig. 11). The production rate is about 24,000 t/year of charcoal from beech wood in seven retorts of this type. Typical



Biomass Pyrolysis. Figure 10
Scheme of a pyroformer

charcoal yield obtained from beech wood is 34%. In addition, 500 t/year of very pure acetic acid can be recovered from this process as well as smoke flavors [30].

An example for an indirect-heated continuous process is the O.E.T. Calusco process.

Wood is transported by trolleys through a horizontal tunnel. The tunnel, 45 m long, is U-shaped. The tunnel is divided in three chambers where the wood is firstly predried, secondly carbonized, and finally cooled down. Each trolley contains 12 m³. The carbonization process is energetically self-sufficient as long as the moisture content of the feedstock is below 45–50% (dry basis). The pyrolysis gases are used to run the process (Fig. 12). The total residence time within the tunnel is 25–35 h depending on moisture content

and feedstock used. The typical production capacity of such a plant is about 6,000 t/year of charcoal [31].

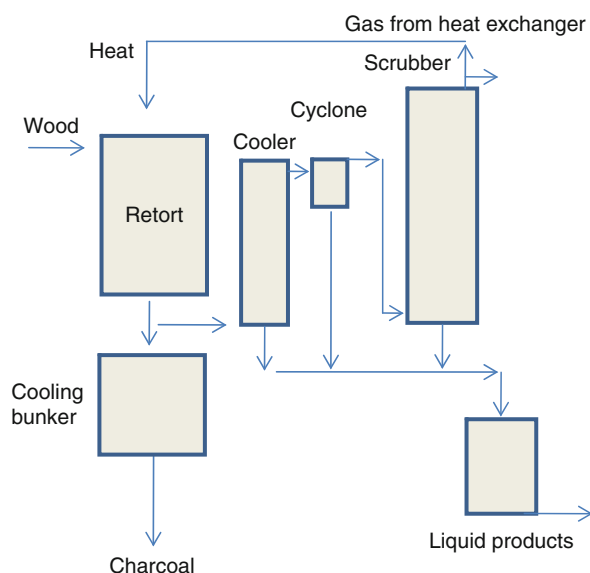
A further selection of charcoal processes is given in [31].

Comparison of Different Pyrolysis Techniques

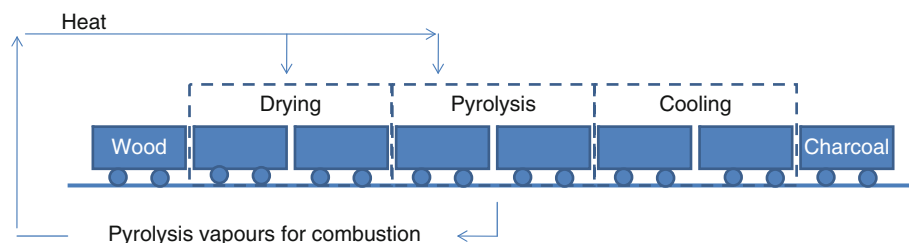
Literature is generally pointing out fast pyrolysis as the measure to turn biomass into maximum amount of liquid and minimum amount of gases. This is true for sure (Table 1 and arrows), but only for wood and is usually leading to one phase liquids high in water, acids, and tars.

In terms of other feedstock like straw, grass, or industrial residues from agricultural products like husks, the picture is much more different. The intermediate pyrolysis offers working conditions preventing formation of high molecular tars and offering dry and brittle chars suitable for different applications like fertilization or combustion. An advantage of this type of processing is the non-milling character and the applicability of larger sized feedstock, which offers the opportunity to separate easily the char from the vapors and to reach a coupled gasifier with low ash feed independent of the ash content of the material before pyrolysis.

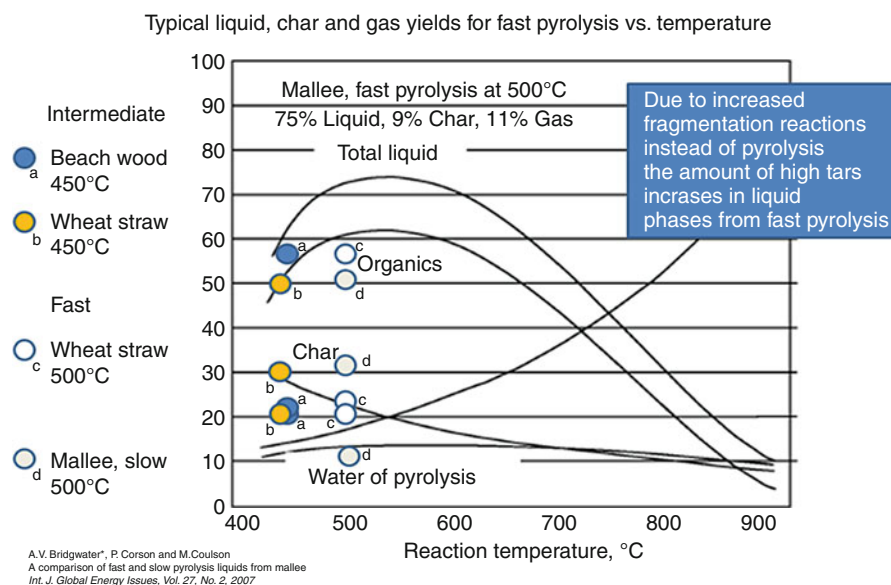
Figure 13 shows the typical behavior of wood during fast pyrolysis at different temperatures. The blue marker (a) shows that even under intermediate pyrolysis conditions, almost similar results can be achieved. Even if two liquid phases are obtained, the total is quite similar. Only if the gas and char yield varies, less char and more gas is produced. Looking at wheat straw, the yellow marker (b) for intermediate pyrolysis and the white marker (c) show a very similar behavior, no longer matching the slopes for wood. The comparison with the gray marker (d) for slow



Biomass Pyrolysis. Figure 11
Degussa process – Chemviron [30]



Biomass Pyrolysis. Figure 12
Principle drawing of the O.E.T. Calusco



Biomass Pyrolysis. Figure 13

Comparison of the yields of liquids from fast, slow, and intermediate pyrolysis [32]

pyrolysis of mallee shows that the intermediate pyrolysis offers a new treatment variety. Compared with fast and slow pyrolysis, similar or more advantageous products can be achieved with less sophisticated technological approaches and therefore lower costs of investment.

Future Directions

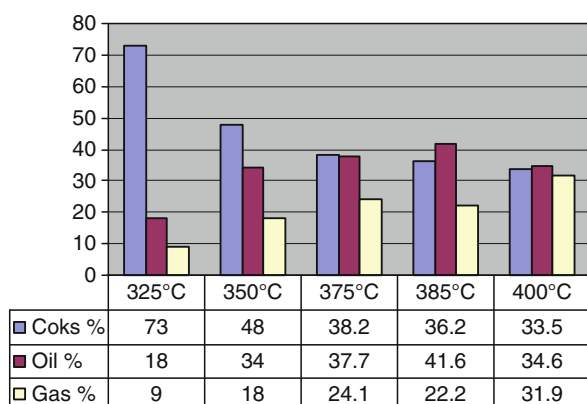
Pyrolysis of biomass is an important process or process element to turn biomass into liquid and gaseous products. Worldwide companies are searching for solutions to liquefy wood and other biomasses to get an intermediate product higher in energy per volume. The sought applications ranging from co-firing and firing in biomass boilers, fuel for gas engines and dual fuel engines to feed of gasifiers. Furthermore, the chemical in the liquids are of interest for bio-refineries as high-value products can be extracted. Finally, the char from pyrolysis is of increasing importance as it can be used to deliver the so-called biochar. Biochar is suitable to fertilize agricultural land and, in addition, sequesters carbon instead of carbon dioxide. Today, the most promising chars for biochar application are delivered by intermediate pyrolysis [33, 34].

Annex 1: Example: Haloclean Pyrolysis and Gasification of Straw

Pyrolysis of straw is still an issue for most of the existing pyrolysis units in the field of fast and slow pyrolysis. The Haloclean process has already been tested in 2005 in a campaign of 5 weeks for the conversion of 15 t of straw into liquids, gas, and char. Later on, the liquids and the char have been successfully converted to synthesize gas in a commercial-scale gasifier [35].

The Haloclean-reactor has been used in a temperature range of 320–500°C. Typical for this reactor are short residence times (1–10 min for the solid residues) for pyrolysis of chaffed straw, finely ground straw, and straw pellets with variable residence times of about 0.3–60 s for the gas phase and gaseous pyrolysis liquids. The Haloclean-reactor consists of a rotary kiln equipped with an internally nitrogen purged and heated screw. During the pyrolysis, metal spheres are transported through the rotary kiln for a better heat transfer.

A very important result of this test is that the shape and size of the feed can be variable without changing the performance of the reactor.



Biomass Pyrolysis. Figure 14

Yield of pyrolysis products – powdered straw

Figure 14 shows that at low temperature (325°C), the coke yield is much higher than the yield of oil (73:18), while at higher temperature (375°C), the ratio coke/oil is 38:37 (1:1). At a pyrolysis temperature of 385°C, the ratio coke/oil is at an optimum of 36:41.6. Therefore, it is possible to obtain with the Haloclean pyrolysis up to 5% more oil than coke.

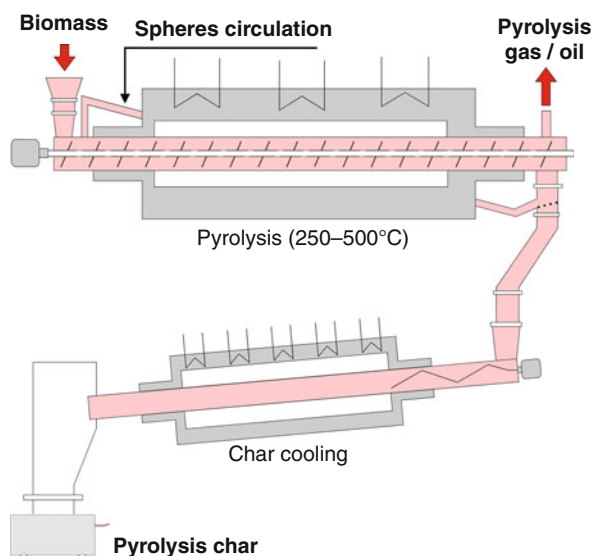
Generally one can see that the amount of pyrolysis gas is increasing with increasing temperature; at 400°C, the amount of pyrolysis oil is decreasing due to the fact that more and more pyrolysis oil is degraded to pyrolysis gas.

The dimensions of the Haloclean-pyrolysis pilot plant are shown in Fig. 15. Below the dimensions of such a plant are given exemplarily.

- Diameter of the pipe: $d_o = 273$ mm, $d_i = 253$ mm
- Length of the oven: 2,200 mm
- Total length: 4,500 mm
- Diameter of the screw: 116 mm
- Draft of the screw: 150 mm
- Heat transfer medium: Spheres $m = 70$ g, $d = 25$ mm

Below, results of the pyrolysis of straw are shown as an example.

- *Pyrolysis Char*: $H_o = 26$ MJ/kg; H_o is the upper heating value
C: 63%, H: 3.7%, N: 1.1%, O: 12.9%
Ash content of the Char: SiO_2 : 59%, Al_2O_3 : 0.3%,
 Fe_2O_3 : 0.7%, CaO: 7.3%, MgO: 2.1%, P_2O_5 : 3.4%, Na_2O : 0.4%, K_2O : 23.8%, SO_3 : 3.1%



Biomass Pyrolysis. Figure 15

Scheme of the Haloclean-pyrolysis pilot plant

- *Pyrolysis Liquid*: $H_o = 7$ MJ/kg (approx. 50% water phase) and 18% highly phenolic phase ($H_o = 24$ MJ/kg)

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Biomass Resources, Worldwide

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Article Outline

Glossary
Definition of the Subject
Introduction
Analysis of Existing Studies
Integration of the Findings
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Conclusions and Future Directions
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Glossary

Biodiversity The variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part, which includes diversity within species, among species, and of ecosystems.

Bio energy Energy derived from biomass.

Biofuel Any liquid, gaseous, or solid fuel produced from plant or animal organic matter (e.g., soybean oil, alcohol from fermented sugar, black liquor from the paper manufacturing process, wood as fuel, etc.). Second-generation biofuels are products such as ethanol and biodiesel derived from lignocellulosic biomass by chemical or biological processes.

Biomass The total mass of living organisms in a given area or of a given species usually expressed as dry

weight. Organic matter consisting of, or recently derived from, living organisms (especially regarded as fuel) excluding peat. Biomass includes products, by-products, and waste derived from such material. Cellulosic biomass is biomass from cellulose, the primary structural component of plants and trees.

Deforestation The natural or anthropogenic process that converts forest land to non-forest.

Ecosystem A system of living organisms interacting with each other and their physical environment. The boundaries of what could be called an ecosystem are somewhat arbitrary, depending on the focus of interest or study. Thus, the extent of an ecosystem may range from very small spatial scales to the entire planet.

Forest Defined under the Kyoto Protocol as a minimum area of land of 0.05–1.0 ha with tree-crown cover (or equivalent stocking level) of more than 10–30% with trees with the potential to reach a minimum height of 2–5 m at maturity in situ. A forest may consist either of closed forest formations where trees of various story and undergrowth cover a high proportion of the ground or of open forest. Young natural stands and all plantations that have yet to reach a crown density of 10–30% or tree height of 2–5 m are included under forest, as are areas normally forming part of the forest area that are temporarily unstocked as a result of human intervention such as harvesting or natural causes but which are expected to revert to forest.

Governance The way government is understood has changed in response to social, economic, and technological changes over recent decades. There is a corresponding shift from government defined strictly by the nation-state to a more inclusive concept of governance, recognizing the contributions of various levels of government (global, international, regional, local) and the roles of the private sector, of nongovernmental actors, and of civil society.

Integrated assessment A method of analysis that combines results and models from the physical, biological, economic, and social sciences, and the interactions between these components in a consistent framework to evaluate the status and the consequences of environmental change and the policy responses to it.

Land use The total of arrangements, activities and inputs undertaken in a certain land-cover type (a set of human actions). The social and economic purposes for which land is managed (e.g., grazing, timber extraction, and conservation). Land-use change occurs when, for example, forest is converted to agricultural land or to urban areas.

Models Models are structured imitations of a system's attributes and mechanisms to mimic appearance or functioning of systems, for example, the climate, the economy of a country, a crop. Mathematical models assemble (many) variables and relations in computer code to simulate system functioning and performance for variations in parameters and inputs. Bottom-up models aggregate technological, engineering, and cost details of specific activities and processes. Top-down models apply macroeconomic theory, econometric and optimization techniques to aggregate economic variables, like total consumption, prices, incomes, and factor costs. Hybrid models include bottom-up approaches or results in top-down models.

Potential Several levels of biomass supply potentials can be identified, although every level may span a broad range.

Market potential The amount of bioenergy output expected to occur under forecast market conditions, shaped by private economic agents and regulated by public authorities. Private economic agents realize private objectives within given, perceived, and expected conditions. Market potentials are based on expected private revenues and expenditures, calculated at private prices (incorporating subsidies, levies, and rents) and with private discount rates. The private context is partly shaped by public authority policies.

Economic potential The amount of bioenergy output projected when all social costs and benefits related to that output are included, there is full transparency of information, and assuming exchanges in the economy install a general equilibrium characterized by spatial and temporal efficiency. Negative externalities and co-benefits of all energy uses and of other economic activities are priced. Social discount rates balance the interests of consecutive human generations.

Sustainable development potential The amount of bioenergy output that would be obtained in an ideal setting of perfect economic markets, optimal social (institutional and governance) systems, and achievement of the sustainable flow of environmental goods and services. This potential is distinct from economic potential by explicitly addressing inter- and intragenerational equity (distribution) and governance issues.

Technical potential The amount of bioenergy output obtainable by full implementation of demonstrated and likely to develop technologies or practices. No explicit reference to costs, barriers, or policies is made. In literature, analysts often adopt practical constraints in that context they implicitly take into account for instance socio-geographical and socio-political considerations (also called resource potential).

Theoretical potential This potential is derived from natural and climatic (physical) parameters. The theoretical potential can be quantified with a reasonable accuracy, but the information is of limited practical relevance. It represents the upper limit of what can be produced from biomass from a theoretical point of view based on current scientific knowledge. It does not take into account energy losses during the conversion process necessary to make use of the resource nor any kind of barriers.

Price elasticity of demand The ratio of the percentage change in the quantity of demand for a good or service to 1% change in the price of that good or service. When the absolute value of the elasticity is between 0 and 1, demand is called inelastic; when it is greater than 1, demand is called elastic.

Reforestation Direct human-induced conversion of non-forested land to forested land through planting, seeding, and/or the human-induced promotion of natural seed sources, on land that was previously forested but converted to non-forested land. For the first commitment period of the Kyoto Protocol, reforestation activities will be limited to reforestation occurring on those lands that did not contain forest on December 31, 1989.

Scenario A plausible description of how the future may develop based on a coherent and internally consistent set of assumptions about key

relationships and driving forces (e.g., rate of technological change, prices) on social, economic, energy, etc. Note that scenarios are neither predictions nor forecasts, but are useful to provide a view of the implications of developments and actions.

Definition of the Subject

The role of biomass as a sustainable source for energy and materials has been heavily debated in recent years. In 2008, when food prices peaked (just as oil and many other commodities), biofuels were blamed for starving the poor, disturbing markets, making unsustainable use of land and water and, especially due to indirect land-use change, resulting in poor or even negative greenhouse gas (GHG) balances. In the meantime, a large amount of literature has been produced providing pieces of insight in various fields, but integral analyses on the matter are scarce. This article provides an extensive assessment of what is known and what is not known about the possibilities to realize a sustainable resource base for bio-based energy carriers and materials. The work looked at energy potentials in conjunction with key factors affecting its sustainability (biodiversity, water, competition with the food production system, soil quality, and energy demand) and deployed integrated assessment modeling plus a detailed evaluation of uncertainties. Biomass energy potentials are found to range between 200 and 500 EJ/year in 2050. Crucial in these figures is that water limitations, biodiversity protection, and food demand are taken into consideration. Improvements of agricultural efficiency and crop choice (especially perennial cropping systems offer the best perspectives) are essential preconditions to reach the higher end of the range.

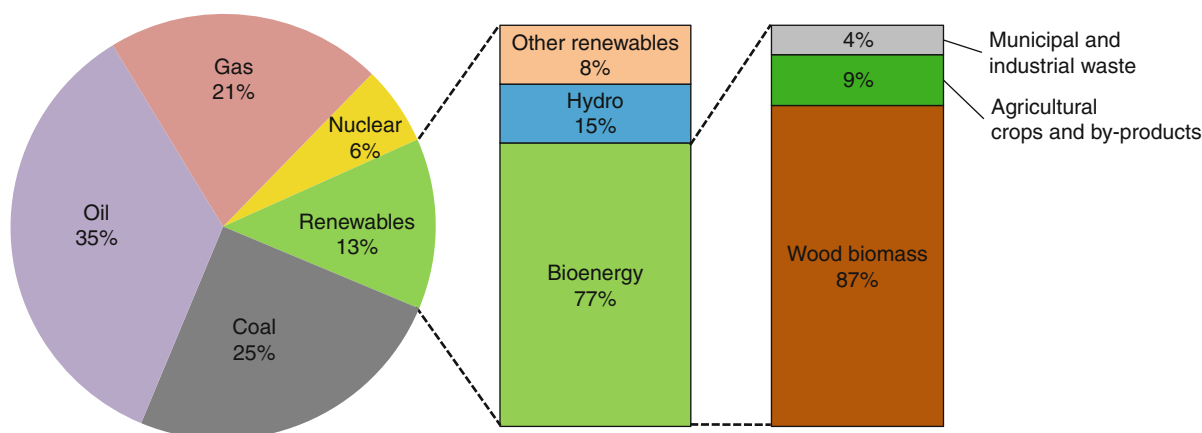
Introduction

In a wide variety of scenarios, policy strategies, and studies that address the future world energy demand and the reduction of greenhouse gas emissions, biomass is considered to play a major role as renewable energy carrier. Over the past decades, the modern use of biomass has increased rapidly in many parts of the world and many countries have ambitious targets for further biomass utilization in the light of the Kyoto GHG reduction targets. Rising oil prices have also increased the level of interest in bioenergy.

Biomass is the most important renewable energy source, providing about 10% (46 EJ) of the annual global primary energy demand. A major part of this biomass use (37 EJ) is noncommercial and relates to charcoal, wood, and manure used for cooking and space heating, generally by the poorer part of the population in developing countries. Modern bioenergy use (for industry, power generation, or transport fuels) is making already a significant contribution of approximately 9 EJ, and this share is growing. Today, biomass (mainly wood) contributes some 10% to the world primary energy mix, and is still by far the most widely used renewable energy source (Fig. 1). While bioenergy represents a mere 3% of primary energy in industrialized countries, it accounts for 22% of the energy mix in developing countries, where it contributes largely to domestic heating and cooking, mostly in simple inefficient stoves.

The expected deployment of biomass for energy on medium to longer term differs considerably between various studies. A key message from the review of currently available insights on large-scale biomass deployment is that its role is largely conditional: deployment will strongly depend on sustainable development of the resource base and governance of land use, on development of infrastructure, and on cost reduction of key technologies, for example, new generation biofuels.

Due to rising prices for fossil fuels (especially oil, but also natural gas and to a lesser extent coal), the competitiveness of biomass use has improved considerably over time. In addition, the development of CO₂ markets (emission trading), as well as ongoing learning and subsequent cost reductions for biomass and bioenergy systems, have strengthened the economic drivers for increasing biomass production, use, and trade. Sufficient biomass resources and a well-functioning biomass market that can assure reliable, sustainable, and lasting biomass supplies are crucial preconditions to realize such ambitions. To date, various countries have considerable experience with building biomass markets and linking available resources with market demand. Examples are found in Brazil, Sweden, Finland, Canada, and the Netherlands. Relatively recently, international trade in biomass resources has become part of the portfolio of market dealers and volumes traded worldwide have



Biomass Resources, Worldwide. Figure 1
Share of bioenergy in the world primary energy mix [1, 2]

increased at a very rapid pace with an estimated doubling of volumes in several markets over the past few years [3].

Because of the “globalization of bioenergy” and the steeply increased demand for both liquid and solid biofuels, biomass supplies (e.g., pellets from agricultural and forest residues, vegetal oils such as palm oil and rapeseed, bio-ethanol) from other continents are now used in various markets. This triggered a heated debate on the sustainability of those developments, because biomass production is now also associated with increased competition with food production and land, loss of forest cover, and the like. Besides such competition, also the net reduction in GHG emissions is questioned in case land use for biomass is associated with clearing (virgin) forest, conversion of peat land, as well as high fossil energy inputs for machinery, fertilizers, and other agrochemicals.

If biomass is to contribute to levels representing up to one third of the global future energy supply during this century, this implies that land-use implications are very significant. Views on such potential developments differ from “utterly destructive” to feasible and possible to develop biomass potentials in synergy with rural development and sustainable management of natural resources. The latter, more positive views, are supported by the fact that rationalization of agriculture has beneficial effects and biomass may also be produced on marginal and degraded lands not suited for production of food, with possible ecological benefits.

Proper standardization and certification procedures to ensure sustainable biomass production and use are currently being developed. Currently, this is a priority for various governments, market players, and international bodies. In particular competition between production of food, preservation of forests and nature, and the use of land for biomass production should be avoided. It is often stated that this may be possible by using lignocellulosic biomass resources that can come from residues and wastes or are grown on non-arable (e.g., degraded) lands and in particular by increased productivity in agricultural and livestock production. Demonstration of such combined development where sustainable biomass production is developed in conjunction with more efficient agricultural management is a challenge and it is questioned to what extent strict sustainability demands will influence biomass resource potentials over time.

The potential for energy crops depends largely on land availability considering that worldwide a growing demand for food has to be met, combined with environmental protection, sustainable management of soils and water reserves, and a variety of other sustainability requirements. Given that a major part of the future biomass resource availability for energy and materials depends on these complex and related factors, it is not possible to present the future biomass potential in one simple figure.

Focusing on the more recent estimates of biomass resource potentials, energy farming on current

agricultural (arable and pasture) land could, with projected technological progress, contribute 100–300 EJ annually, without jeopardizing the world's future food supply. A significant part of this potential (around 200 EJ in 2050) for biomass production may be developed at low production costs in the range of 2 €/GJ assuming this land is used for perennial crops [4, 5]. Another 100 EJ could be produced with lower productivity and higher costs, from biomass on marginal and degraded lands. Regenerating such lands requires more upfront investment, but competition with other land uses is less of an issue and other benefits (such as soil restoration, improved water retention functions) may be obtained, which could partly compensate biomass production costs. Combined and using the more average potential estimates, organic wastes and residues could possibly supply another 40–170 EJ, with uncertain contributions from forest residues and potentially a significant role for organic waste, especially when biomaterials are used on a larger scale.

Key to the introduction of biomass production in the suggested orders of magnitude is the rationalization of agriculture, especially in developing countries. There is room for considerably higher land-use efficiencies that can more than compensate for the growing demand for food [6].

Available studies already indicate that the results are sensitive to assumptions about crop yields and the amount of land that could be made available for the production of biomass for energy uses, including biofuels. Critical issues include:

- *Competition for water resources:* Although the estimates mentioned above generally exclude irrigation for biomass production, it may be necessary in some countries where water is already scarce.
- *Use of fertilizers and pest control techniques:* Improved farm management and higher productivity depend on the availability of fertilizers and pest control. The environmental effects of heavy use of fertilizer and pesticides could be grave.
- *Land use:* More intensive farming to produce energy crops on a large scale may result in losses of biodiversity. Perennial crops are expected to be less harmful, or even able to achieve positive effects compared to conventional crops such as cereals and seeds. More intensive cattle-raising would also

be necessary to free up grassland currently used for grazing.

- *Competition with food and feed production:* Increased biomass production for biofuels out of balance with required productivity increases in agriculture could drive up land and food prices.

Although available studies give a reasonable insight in the importance of various parameters, the integration between different arenas is still relatively limited. This causes confusion in public as well as scientific debate, with conflicting views on the possibilities for sustainable use of biomass as a result. These explanations aim to tackle this problem by providing a more comprehensive assessment of the current knowledge with respect to biomass resource potentials.

The main objectives of this work are outlined below.

1. Provide clear insights in the linkages between the impacts of (large-scale) use of biomass for energy and material on food supplies, water use, nature and biodiversity, and in macroeconomic terms.
2. Provide insight in regional and site-specific elements in the above-mentioned issues.
3. Translate the results of the assessment into an overview of the more and less certain issues with respect to biomass resource potentials and to policy-relevant recommendations on how to develop and use biomass resources in a sustainable way, including research and development needs.

To reach these goals the work is set up as follows.

- The first part comprises an assessment of recent literature on the key areas distinguished: biomass potentials, food production, water, biodiversity, energy demand, and analyses of agricultural economics. Furthermore, greenhouse gas (GHG) balances of biomass use for energy are distinguished as a separate topic. Distinction is made between various biomass resource-technology combinations and different settings for biomass production.
- The second part is an integration component, which describes the linkages between the different key areas and quantifies the consequences of the results of the assessment to the extent that available models and tools allow doing so. A limitation is that no new models are developed.

- The third part translates the results of the assessment and the integration activities into an extensive assessment of the uncertainties of future biomass resource potentials and which factors are of major and which of lesser importance. Based on this, policy recommendations and further steps to reduce uncertainties and fill gaps in knowledge are identified.

Analysis of Existing Studies

Here, a summary is given of the review of recent studies in the field of biomass potentials, biodiversity, water, food demand, energy demand, and agricultural economics. These are main relevant areas for estimating the potentials of biomass for energy and material purposes.

The review describes the most important aspects and parameters that should be taken into account in an “ideal study.” Common to all areas is that global trends on population growth and economic development are an important basis to estimate future development. Within the review, the key parameters on the current situation and on the future developments that resulted from the various studies are presented. Finally, conclusions are drawn regarding important relations of the separate areas with biomass potentials and possible knowledge gaps.

Biomass Potential Studies

Earlier analyses of biomass potential studies had shown large ranges of outcomes that were based on differences in methodologies and assumption on crop yields and available land and in the case of economic potentials on differences in the estimated production costs [7].

An “ideal” study to evaluate biomass potentials should take into account global and regional trends and specific local conditions such as soil types, water availability, possibility of irrigation, and land-use planning taking biodiversity and soil quality into account. It is expected that moving to the large-scale use of biomass for energy and materials will change land-use patterns and energy systems significantly. Such changes would influence supply and demand of (agricultural) land as well as those of food, materials, wood products, and energy carriers in a dynamic way. The economic relationships between the demand and the supply of biomass, especially taking into account changes of land

and food prices on a regional to local level, should therefore be considered.

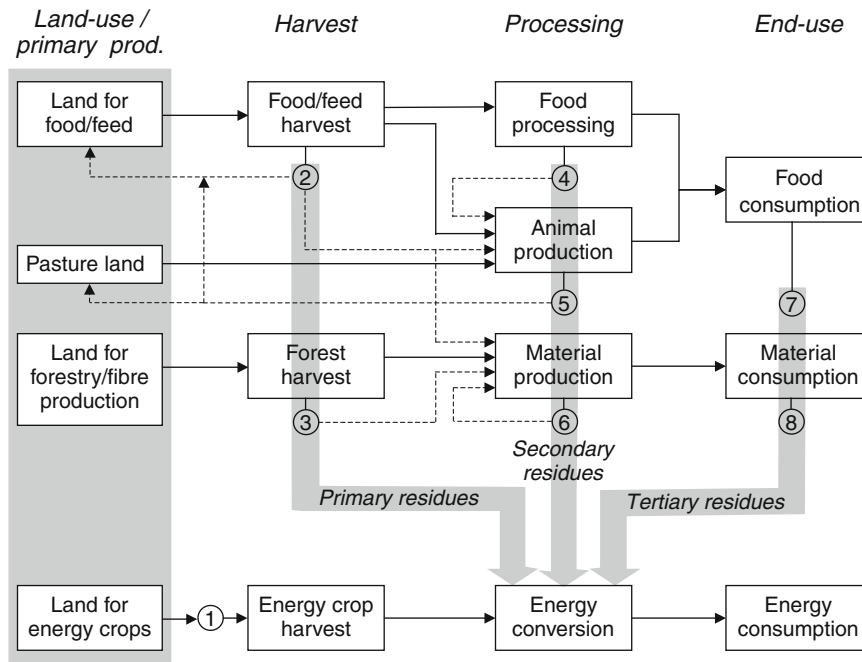
This section focuses on the potential availability of biomass resources for energy and materials. It briefly discusses the various resource categories: residues from forestry and agriculture, various organic waste streams and, most important, the possibilities for active biomass production on various land categories (e.g., for wood plantations or energy crops such as sugar cane) (Fig. 2).

Biomass residues potential availability is discussed below. These may be divided into:

1. Primary residues: residues generated pre- and at harvest of main product, for example, tops and leaves of sugar cane
2. Secondary residues: residues generated in processing to make products, for example, bagasse, rice husks, and black liquor
3. Tertiary residues: residues generated during- and post end use (+ non-used products), for example, demolition wood and municipal solid waste

In general, biomass residues (and wastes) are intertwined with a complex of markets. Many residues have useful applications such as fodder, fertilizer and soil conditioner, and raw material, for example, for particle board, medium density fiber board (MDF), and recycled paper. Net availability as well as (market) prices of biomass residues and wastes therefore generally depend on market demand, local as well as international markets for various raw material, and on the type of waste treatment technology deployed for remaining material. The latter is particularly relevant when waste treatment is paid for giving some organic waste streams a (theoretical) negative value. Typically, the net availability of organic wastes and residues can fluctuate and is influenced by market developments, but also can depend on climate (high and low production years in agriculture) and other factors.

Energy crops are planted on agricultural or other lands for energy and material purposes. In practice there exists a competition between land used for energy crops, animal grazing, forestry, and food. However, synergy exists between these sources; the growth in food and forestry products directly implies increased amounts of crop residues with potential use for energy purposes.



Biomass Resources, Worldwide. Figure 2

Schematic overview of the present terrestrial biomass flows in the food, materials, and bioenergy sectors, as well as in final end use. The gray arrows denote: (1) energy crops, (2) agricultural residues, (3) forest residues, (4) food residues, (5) manure, (6) non-food organic waste, (7) food consumption waste, and (8) non-food consumption waste [9]

Residues and Wastes Vast amounts of biomass residue exist that could potentially be used as feedstock for biofuel production. Much of the plant matter produced by common crops is left on the fields after harvest, and a large portion of this decomposes into carbon dioxide rather than returning to the soil. Similarly, forestry practices leave behind large quantities of unharvested wood, and fire mitigation practices have allowed forest underbrush to accumulate. Of the biomass that is already being harvested, large amounts of residues are generated at agricultural processing facilities and forestry mills, including sugar cane bagasse, rice hulls, nut shells, saw dust, and black liquor (at paper mills). In urban areas, cellulosic residues include portions of municipal solid waste, grass clippings, and wood from tree trimmings and land clearing activities.

Residues and wastes have several advantages over dedicated energy crops. Most of them would require no additional land acreage, as they are typically pre-collected into piles at large agricultural and forestry facilities and often represent “waste” that must

otherwise be disposed of. As a result, this feedstock is cheaper and is likely to be the first source of biomass to be tapped. Already, the wood products industry uses most lumber residues and much of the forestry residue in Europe and the USA for processing purposes and to generate coproducts such as wood chips, fiberboard, etc.

For sustainability reasons, however, estimates of potential bioenergy from waste and residues would likely be lower than those suggested above. In general, it is a good idea to retain some portion of biomass residue in the field or forest to hold carbon, water, and other nutrients in the soil, and to provide habitat for various species. Leaving a protective amount of residue behind is especially important on steep slopes or on ecologically sensitive sites that have particularly erodible soils, or are near riparian areas.

Residues from Agriculture The production potential for agricultural residues depends on the various yields of different agricultural products, the total agricultural

land area, and the type of production system. Less-intensive management systems require the reuse of residues for maintaining soil fertility, reducing the total amount that can be sustainably removed. More intensively managed systems, meanwhile, allow for higher use rates of residues but also typically rely on crops with lower crop-to-residue ratios, such as corn.

Estimates are available from various studies. Potential depends on yield/product ratios and the total agricultural land area as well as type of production system. Less-intensive management systems require reuse of residues for maintaining soil fertility. Intensively managed systems allow for higher utilization rates of residues but also usually deploy crops with lower crop-to-residue ratios. Estimates vary between some 15 and 70 EJ/year. The latter figure is based on the regional production of food (in 2003) multiplied by harvesting or processing factors and the assumed recoverability factors [6]. These figures do not subtract the potential alternative use for agricultural residues. But, competing applications can reduce the net availability of agricultural residues for energy or materials significantly [8].

Dung This category especially concerns the use of dried dung. Total estimated contribution could be 5–55 EJ/year worldwide. The low estimate is based on global current use, and the high estimate is the technical potential. Utilization (collection) in the long run is uncertain because this is particularly considered a poor man's fuel [9]. There are also sociocultural constraints in waste utilization, which explain somewhat the wide differences in waste utilization across different regions and cultures.

Organic Wastes This category includes the organic fraction of municipal solid waste (MSW) and waste wood (e.g., demolition wood). Organic wastes are a particularly attractive source of biomass energy because they can have a “negative” price. In other words, collecting and utilizing can result in savings from landfill tipping fees. Estimates on the basis of literature values strongly depend on assumptions regarding economic development, consumption, and the use of biomaterials; the ranges projected for MSW in the long run (e.g., beyond 2040) amount to 5–50 EJ/year. Higher values are possible when more intensive use is made of biomaterials [9, 10].

Forest Residues The (sustainable) energy potential of the world's forests is partly uncertain. A recent evaluation of forest reserves and development of demand for wood products concluded that even in the case of the highest wood demand projections found in literature, the demand can (in theory) be met without further deforestation. The bioenergy potential from forestry can contribute 1–98 EJ/year of surplus natural forest growth and 32–52 EJ/year harvesting and processing residues in 2050. The most promising regions are the Caribbean and Latin America, the former Soviet Union, and partially North America. Key variables are the demand for industrial round wood and fuel wood, plantation establishment rates, natural forest growth, and the impact of technology and recycling [11].

Despite this potential, the amount of energy that can be obtained from forest residues and other waste biomass resources will be limited in comparison to energy crops; moreover, these reserves will likely be depleted first as demand for bioenergy grows. Finland, which has focused on harnessing biomass energy for many years, has already used a large part of its accessible residues and wastes and is now importing wood energy.

Energy Crops Biomass production requires land. Conservatively, the productivity for a perennial crop (like Willow, Eucalyptus, or Switchgrass) lies between 8 and 12 t dry matter per hectare per year. The heating value of dry clean wood amounts to about 18 GJ/t (LHV). One hectare of planted area can therefore produce about 140–220 GJ/(ha year) (gross energy yield, energy inputs for cultivation, fertilizer, harvest, etc., amount to about 5%).

One petajoule would require 4,500–7,000 ha; 1,500 MW_{th} (the amount of fuel needed to fire a base load power plant with 40% efficiency of 600 MW_e) would require 140,000–230,000 ha; and 100 EJ (about one quarter of the world's current energy use) would ask 450–700 Mha.

The potential for energy crops therefore largely depends on land availability considering that worldwide a growing demand for food has to be met, combined with nature protection, sustainable management of soils and water reserves, and a variety of other sustainability criteria. Given that a major part of the

future biomass resource availability for energy and materials depend on these (intertwined, uncertain, and partially policy dependent) factors, it is impossible to present the future biomass potential in one simple figure.

Review of Studies In this assessment, the focus is laid on the relation between estimated biomass potentials and the availability and demand of water, the production and demand of food, influence on biodiversity, and economic mechanisms. For this purpose, eight recent studies are analyzed (Table 1). None of these studies covers the whole range of issues, but they all have strong points at certain issues.

The scope of the studies, in terms of biomass resources included, varies as well as the scenario assumptions. As a consequence, global biomass potentials vary widely. The high biomass potential for 2050 determined by Smeets et al. [6] shows potentials under intensive, very high technologically developed agriculture. On the contrary, the low biomass potential for 2050 calculated by Wolf et al. [17] is caused by high population growth, high food demands, and extensive agricultural production systems. The study of Hoogwijk et al., 2005, refers to production of energy crops on abandoned, marginal, and rest land assuming global and regional trends as described in the IPCC SRES scenarios, under increasing agricultural efficiency over time [13]. Finally, the study of Rokityanski et al. determines economic potentials of afforestation and reforestation, excluding other types of biomass and assuming extensive forestry management [16]. As a result, the economic potentials for 2100 are rather low.

Most earlier assessments of biomass resource potentials used rather simplistic approaches to estimating the potential of biomass plantations [7], but the continuous development of modeling tools that combine databases containing biophysical information (soil, topography, climate) with analytical representations of relevant crops and agronomic systems has resulted in improvements over time (see, e.g., [18, 19, 20, 21, 22]).

Table 2 shows ranges in the assessed resource potential year 2050, explicit for various biomass categories. The ranges (based on [6, 9, and 13]) provide a summary of the biomass categories discussed. A large

number of studies (e.g., [23, 24, 25]) were reviewed that assess the global and regional potential, and on selected additional studies not included in these reviews ([6, 10, 19, 26–29]).

The wide ranges in Table 2 are because the studies differ in their approach to considering different determining factors, which are in themselves uncertain: Population, economic, and technological development can go in different directions and pace; biodiversity and nature conservation requirements set limitations that are difficult to assess; and climate change as well as land use in itself can strongly influence the biophysical capacity of land. Biomass potentials can also not be determined exactly as long as uncertainty remains about agreed trade-offs with respect to additional biodiversity loss or intensification pressure in food production as well as potential synergies in land use.

Conclusions Summarizing, both the technical and economic potential of biomass resources for energy and material use can be very large, up to over two times the current global energy demand, without competing with food production, protection of forests and nature. Besides residues from agriculture and forestry (which are significant, but also limited due to competing applications), organic waste and the active production of biomass (e.g., energy crops) are the two main factors responsible for these potentials. Key, however, to the development of competitive energy cropping systems is the rationalization of agriculture, especially in developing countries, which can result in considerably higher land-use efficiencies for agriculture and, thus, a surplus of productive land. Perennial crops (such as Eucalyptus, poplar, grasses as *Miscanthus* and sugar cane) provide the most favorable economics and environmental characteristics for biomass production. Table 2 provides a summary of the biomass categories discussed in this section.

In theory, energy farming on current agricultural land could, with projected technological progress, contribute over 800 EJ, without jeopardizing the world's food supply. Organic wastes and residues could possibly supply another 40–170 EJ, with uncertain contributions from forest residues and potentially a very significant role for organic waste, especially when biomaterials are used on a larger scale. In total, the upper limit the of bioenergy potential could be over

Biomass Resources, Worldwide. Table 1 Overview and evaluation of selected biomass potential studies

Study	Subject	Biomass potential	Evaluation
Fischer et al. [12]	Assessment of ecophysiological biomass yields	CEE, North and Central Asia; EC (poplar, willow, <i>Miscanthus</i>); TP	<i>Strong</i> : detailed differentiation of land suitability for biomass production of specific crops on a grid-cell level (0.5 degree) <i>Weak</i> : not considering interlinkages with food, energy, economy biodiversity, and water demands
Hoogwijk et al. [13]	Integrated assessment based on SRES scenarios	Global, EC (short-rotation crops); TP	<i>Strong</i> : integrated assessment considering food, energy material demands including a scenario analyses based; analyses of different categories of land (e.g., marginal, abandoned) <i>Weak</i> : crop yields not modeled detailed for different species and management systems
Hoogwijk et al. [4]	Cost-supply curves of biomass based on integrated assessment	Global; EC (short-rotation crops; TP, EP (as cost-supply curve)	<i>Strong</i> : establishes a global cost-supply curve for biomass based on integrated assessment <i>Weak</i> : linkage land/energy prices not regarded
Obersteiner et al. [14]	Biomass supply from afforestation/ reforestation activities	Global; F (incl. short-rotation); EP	<i>Strong</i> : modeling of economic potential by comparing net present value of agriculture and forestry on grid-cell level <i>Weak</i> : yields of forestry production not dependent on different technology levels
Perlack et al. [15]	Biomass supply study based on outlook studies from agriculture and forestry	USA; EC, F, FR, AR, SR, TR; TP	<i>Strong</i> : detailed inclusion of possible advances in agricultural production systems (incl. genetic manipulation) <i>Weak</i> : no integrated assessment, e.g., demands for food and materials not modeled
Rokityanski et al. [16]	Analysis of land-use change mitigation options; methods similar to Obersteiner et al. [14]	Global; F (incl. short-rotation); EP	<i>Strong</i> : policy analysis of stimulating land-use options including carbon prices <i>Weak</i> : agricultural land not included
Smeets et al. [6]	Bottom-up assessment of bioenergy potentials	Global; EC, F, AR, FR, SR, TR; TP	<i>Strong</i> : detailed bottom-up information on agricultural production systems including animal production <i>Weak</i> : yield data for crops only regionally modeled
Wolf et al. [17]	Bottom-up assessment of bioenergy potentials mainly analyzing food supplies	Global; EC; TP	<i>Strong</i> : various scenarios on production systems and demand showing a large range of potentials <i>Weak</i> : yields of energy crops not specified for different species and land types

Biomass: EC energy crops, F forestry production, FR primary forest residues, AR primary agricultural residues, SR secondary residues, TR tertiary residues

Potentials: TP technical potential, EP economic potential

Biomass Resources, Worldwide. Table 2 Overview of the global potential bioenergy supply on the long term for a number of categories and the main preconditions and assumptions that determine these potentials

Biomass category	Main assumptions and remarks	Potential bioenergy supply up to 2050
Energy farming on current agricultural land	Potential land surplus: 0–4 Gha (more average: 1–2 Gha). A large surplus requires structural adaptation of intensive agricultural production systems. When this is not feasible, the bioenergy potential could be reduced to zero as well. On average higher yields are likely because of better soil quality: 8–12 dry t/ha year is assumed ^a	0–700 EJ (more average development: 100–300 EJ)
Biomass production on marginal lands	On a global scale a maximum land surface of 1.7 Gha could be involved. Low productivity of 2–5 dry t/ha year ^a . The supply could be low or zero due to poor economics or competition with food production	(0) 60–150 EJ
Biomaterials	Range of the land area required to meet the additional global demand for biomaterials: 0.2–0.8 Gha (average productivity: 5 dry t/ha year). This demand should come from category I and II in case the world's forests are unable to meet the additional demand. If they are, however, the claim on (agricultural) land could be zero	Minus (0) 40–150 EJ
Residues from agriculture	Estimates from various studies. Potential depends on yield/product ratios and the total agricultural land area as well as type of production system: Extensive production systems require reuse of residues for maintaining soil fertility. Intensive systems allow for higher utilization rates of residues	Approx. 15–70 EJ
Forest residues	The (sustainable) energy potential of the world's forests is unclear. Part is natural forest (reserves). Range is based on literature data. Low value: figure for sustainable forest management. High value: technical potential. Figures include processing residues	(0) 30–150 EJ
Dung	Use of dried dung. Low estimate based on global current use. High estimate: technical potential. Utilization (collection) on longer term is uncertain	(0) 5–55 EJ
Organic wastes	Estimate on basis of literature values. Strongly dependent on economic development, consumption, and the use of biomaterials. Figures include the organic fraction of MSW and waste wood. Higher values possible by more intensive use of biomaterials	5–50 (+) EJ ^b
Total	Most pessimistic scenario: no land available for energy farming, only utilization of residues. Most optimistic scenario: intensive agriculture concentrated on the better quality soils (more average potential in a world aiming for large-scale utilization of bioenergy)	40–1,100 EJ (250–500 EJ)

^aHeating value: 19 GJ/t dry matter

^bThe energy supply of biomaterials ending up as waste can vary between 20 and 55 EJ (or 1,100–2,900 Mt dry matter per year (see Table 4); biomass lost during conversion, such as charcoal is logically excluded from this range). This range excludes cascading and does not take into account the time delay between production of the material and “release” as (organic) waste

1,000 EJ/year [6, 9]. This is considerably more than the current global energy use of about 500 EJ.

Latin America, sub-Saharan Africa, and Eastern Europe clearly are the most promising regions, as well as Oceania and East and Northeast Asia (in the future). The latter can in particular be explained by the

projected demographic developments (possibly declining population in China after 2030) and fast technological progress in agriculture, leading to substantial productivity increases.

These analyses also show that a large part of the technical potential for biomass production may

be developed at low production costs of around 2 USD/GJ [4]. Major transitions are however required to exploit this bioenergy potential, especially improving agricultural efficiency in developing countries (i.e., increasing crop yields per hectare). It is still uncertain to what extent and how fast such transitions can be realized in different regions. Under less favorable conditions, the (regional) bioenergy potential(s) could be quite low.

Also, it should be noted that technological developments in conversion, as well as long distance biomass supply chains (i.e., comprising intercontinental transport of biomass derived energy carriers), can dramatically improve competitiveness and efficiency of bioenergy. Increased competitiveness is logically a driver to develop the production potentials of bioenergy.

The recent biomass potential studies give more detailed and well-founded insights into future biomass potentials, but none of the studies does include all critical aspects. Important issues that remain unresolved are:

- The competition for water with other economic sectors, as well as the possibilities of irrigation, has not been included in the biomass potential studies.
- Human diets and alternative protein chains have been included to a limited extent only in the potential estimates, while the impacts of different animal production systems need to be studied in more detail and applied to more biomass potential studies.
- The demand for wood products and other biomaterials has been simplified in most studies and has not been modeled based on economic scenario analysis.
- The impact of large-scale biomass production on the prices (and subsequently) demands of land and food has not been sufficiently studied.
- The impact of specific biodiversity objectives on biomass potentials has not been investigated in detail.

These issues are discussed in more detail in the following sections.

Biodiversity

The global number of species has shown a fast decrease in the last few centuries, mostly through

habitat loss and land-use change. The raised policy interest has led to two global UN Conventions that contain targets on preventing further biodiversity decline. The CBD Convention wants to reduce the rate of further loss by 2010, and is focused on a broad range of causes for the decline, among which land use changes. The Climate Convention (UNFCCC) has a long-term goal to prevent damage to biodiversity from climate change effects, next to mitigating climate change itself.

Designing policy options and measures that may help to reach these short- and long-term targets (such as climate change mitigation through use of bioenergy) depend on the way the concept of biodiversity is implemented. Biodiversity includes the variability of all living organisms and all ecosystems. It is a complex phenomenon and cannot be simply defined and measured. All possible indicators are imperfect to capture the full complexity, but they are useful if they can be monitored and explained, related to human impact, and modeled to show future developments and the effects of policy choices. Several complementary indicators are therefore used within the CBD framework. Different indicators might give different messages because of different definitions and implicit valuation of biodiversity, for instance when indicators based on “naturalness” or contrarily on “agro-biodiversity” are used.

Bioenergy potential studies conducted so far mostly neglect the effects of biofuel production on different biodiversity indices. An ideal study should take all relevant biodiversity aspects and scales into account, and should not only show local effects, but possible shifts and trade-offs to other locations as well. Several types of impact assessment studies can be distinguished:

1. Assessing local and present impacts of bioenergy cultivation
2. Assessing integral, global impacts of bioenergy in an LCA-approach, comparing the effects of biofuels and fossil fuels over the whole production chain on greenhouse gas emissions, land use, and biodiversity effects
3. Regional and global scenario studies, showing the integral and future effects of bioenergy, in combination with other global developments in

population growth, food demand, diets, and agricultural productivity

Review of Studies For local impact studies, locally specific aspects like irrigation, fertilizer and pesticide use, former land use, and landscape structure are important. When still natural areas are converted for bioenergy production, natural biodiversity is obviously lost. In case energy crops are just an additional element in agricultural rotation systems local short-term effects are negligible. On the other hand, agro-biodiversity is at risk when extensively used low input farmlands are converted to biomass crops. In Europe, protecting this type of biodiversity is a policy objective in its own. Positive effects for local biodiversity are also possible, for instance when replacing intensively managed agricultural systems by extensively managed perennial crops; or when replacing monocultures by extensively used mixed systems (agroforestry, mixed cropping, organic farming).

In LCA-studies, the global and integral impact of biofuels on biodiversity depends strongly on the following aspects:

- The integral reduction of greenhouse gas emissions (with fossil fuels as a reference, but also comparing different applications of the same biomass) per hectare of land used, depending on technology, soil characteristics, and climate. Liquid biofuels based on perennial and woody crops as well as sugarcane ethanol and palm oil generally provide better results than European crops. However, changes in land use might lead to an increase of CO₂ emissions in case carbon is released from the soil.
- The loss of biodiversity related to specific land-use changes. In general the cultivation of natural areas leads to significant loss. In case of the cultivation of abandoned land the effect in time depends on the restoration time of biodiversity values. The values of cultivated land depend on management practices and crop type.
- The (reduced) long-term effect of climate change on biodiversity, which is hard to quantify because of high uncertainties on the long term. For most liquid biofuels the overall impact on biodiversity is very likely to be negative. For none of the biofuels a positive impact can be guaranteed.

There are no global scenario studies that take all relevant aspects of the biofuel debate into account. Several issues were treated in a global study [30, 31]. The analysis contained an ambitious climate change option with a broad measure portfolio, including large-scale use of bioenergy. The aggregated indicator MSA (“mean abundance of original species”) was applied to express global biodiversity loss, which can be interpreted as a measure of naturalness or ecosystem intactness. The indicator is not intended to highlight individual species, agro-biodiversity, or the specific value of protected areas. The analysis indicated that increased land use of mainly abandoned land and marginal grounds for growing bioenergy crops leads to biodiversity losses on the short term (as compared to a baseline scenario, in which abandoned lands will restore to a more-or-less natural situation). By 2050, the increased loss is not yet counteracted by biodiversity gains through avoided climate change. In determining whether short-term losses can be balanced by long-term gains, uncertainty should be taken into account. Long-term effects are based on modeling exercises that are surrounded with considerable conceptual and data uncertainty. The local and specific characteristics and biodiversity values of the economically defined “marginal grounds” are also not well known. Further, there is uncertainty on the assumption on fast and complete biodiversity restoration on abandoned land.

Conclusions Published studies on the biodiversity effects of growing bioenergy crops are very diverse and show opposite results. These differences are the result of using different time horizons (short and/or long term), different scales of observation (local, regional, or global), and the different biodiversity definitions (for instance naturalness or agro-biodiversity). More often than not, the used biodiversity indicators are not explicitly defined.

The integral global impacts of biofuels on biodiversity depend mainly on the long-term positive effect of reduced future climate change and the short-term negative effect of land-use change for large-scale energy crop cultivation instead of nature. In determining whether short-term losses can be balanced by long-term gains, uncertainties should be taken into account. The short-term effects have a high degree of confidence

as the effects of local land-use change are based on monitored effects, while long-term effects are based on modeling exercises that are surrounded with considerable conceptual and data uncertainty. This finding shows that it is not easy to combine both the short-term CBD biodiversity goals and the long biodiversity goals of the Climate Convention.

In all cases a negative impact results from additional land use for large-scale biomass production. European annual agricultural crops do worse at the local level than tropical and perennial and woody crops. Further, not all biodiversity indicators might show the same results, especially when agro-biodiversity and naturalness are confronted. Specifically, the uncertainties about the future beneficial effects of reduced climate change on biodiversity make it hard to draw definite conclusions about the long-term impact of biofuels.

Water

Quantification of the spatial and temporal distribution of river runoff and assessing the influence of humans form the backbone for decisions on optimal use of water resources. A common classification of water resources is the classification into blue and green water flows. Blue water refers to water in rivers, lakes, and groundwater. Green water refers to water in the rooted zone of the soil originating directly from rainfall that is available to plants. Globally around 80% of agricultural evapotranspiration (crop water depletion) originates from green water, while the remaining 20% is provided through irrigation (blue water withdrawals) [32]. Twenty to fifty percent of blue water, depending on the local situation, is required for environmental requirements and services. In addition, water is required for industrial and domestic use.

At the regional and local scale, for blue water irrigation efficiency is a major determinant of water use. It is often defined as the net crop water requirement for evapotranspiration as part of the water withdrawn from a water source. A typical value would be 40%. Most of the other 60% is captured and recycled somewhere else in the system. As reuse loops of water are very common in river basins, improving irrigation efficiency becomes a very complex issue. Water productivity (WP) indicates the efficiency of water use, including blue water, if irrigated, and green water. Crop

water productivity (CWP) is an indicator of crop yield per unit of water consumed (evapotranspiration). This implies crop water productivity depends on the main product. If the plant parts used for energy and food are not the same, crop water productivity of a crop differs for both purposes. Water use by crops can be estimated based on weather data and crop growth modeling or by a crop-specific water use efficiency (WUE) that varies among crops and crop types (C_3 – C_4 crops, annuals – perennials, herbaceous – woody species) and also with weather (rainfall, temperature, radiation) and agricultural management, such as input use and other practices. Water use efficiency can refer to evapotranspiration, transpiration, total crop yield, economic product, etc. Hence, caution is required when using data from literature [33].

The ideal study does not exist as several very divergent aspects have to be considered with respect to water. Water availability and water use can be assessed at crop, farm, river basin, continental, and global scales. Each scale has its own crucial parameters for reliable calculations and estimates and its own assessment targets. Water use for bioenergy production has to be compared with actual water (and nutrient) use and existing or expected bottle necks for water availability have to be identified. As priority is often given to the other uses (food, domestic and industrial water use), all uncertainties and inaccuracies are accumulating in the final assessment of the scope for energy crops.

Review of Studies Expected future water use by industry and domestic sectors differs between different sources, as assumptions on technological development (efficient systems), economy, and lifestyle vary among these sources. Some studies expect it to be more or less constant [34] and others expect it to increase by 60–220% [35]. However, the largest part of this use (80%) flows back to rivers, lakes, or groundwater. For agricultural water withdrawal, estimates vary considerably depending on the scenarios on population growth, human diet, and input levels used. However, in all scenarios total water use is increasing. Energy crops are not considered explicitly in most studies.

The effect of expanding the area under biomass crops taking into account both rain-fed and irrigated agriculture can be estimated [13, 17]. If the area available for energy crops varies between 0% and 45% of the

present agricultural land (depending on the assumed scenario; i.e., human diet, input level, and population growth [36]), under a biomass-intensive scenario similar trends can be expected for energy crops as other studies showed for food crops. But the effect is stronger: increasing water scarcity in most regions, with the largest effects in the regions that are already water scarce. Increasing evapotranspiration is the main factor and irrigation of energy crops would increase water scarcity.

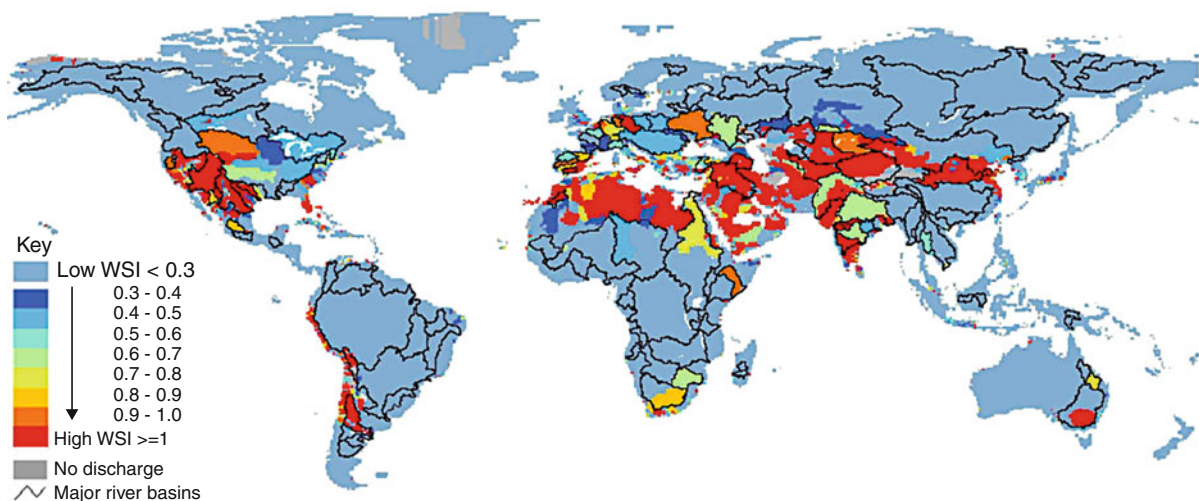
Total blue water requirements and availability, including the environmental water requirements (EWR) have been expressed in a water stress indicator (Fig. 3) [32, 35, 37].

All studies give solutions or directives for improving water use efficiency at given scales, both for irrigated and rain-fed agriculture. It is generally acknowledged that considerable improvements can potentially be realized. Measures to alleviate water stress include increased recycling of industrial and domestic water, change of diets toward less-water-consuming foods and less meat, improve agricultural water productivity by reducing runoff, water harvesting, supplemental irrigation, and better maintenance of irrigation systems; the latter measures specifically increase the use efficiency of blue water.

At the field scale, high water use efficiency (WUE) of crops can only be achieved if other factors (nutrient

availability, incidence of pests and diseases, appropriate and timely management) are not limiting crop production to a larger extent than water. In that case, evaporation (unproductive water loss) is minimized and transpiration (productive water use) is maximized. Hence, optimal input use and soil management increase the efficiency of green (and blue) water use. In different regions of the world large variations in actual crop water use efficiency are reported resulting from variations in these factors [32]. Hence, in estimating opportunities for energy crops, the strong interaction between water, nutrients, and management has to be taken into account. In practice, crop production systems in a region, steered by local climatic, edaphic, economic, and social conditions, show large differences in input use and efficiency as compared to otherwise comparable systems in other regions.

Climate change is very likely to change rainfall patterns while increasing temperatures will influence water transpiration and evaporation. The net effect is not easy to predict and will show large variations among different regions of the world. Especially, semi-arid and arid areas are expected to suffer from reduced water availability caused by a combination of increasing precipitation variability, increased water use by crops, and reduced groundwater recharge. Problems are further expected in river basins depending on glacier or snowmelt-fed rivers while sea-level rise may lead



Biomass Resources, Worldwide. Figure 3
Water stress indicators [37]

to increased salinization of groundwater and estuaries. While positive effects of climate change on freshwater systems will occur, on the whole, negative effects will outweigh the benefits. There are signs that the impact on irrigation systems may be very strong, generally limiting irrigation water potential.

Conclusions Comparing the different analyses shows that problems are analyzed at a higher scale than the solutions formulated. The large variability in regional climate and hydrology asks for a detailed and local analysis of the biophysical possibilities for crop production. The studies analyzed show that conditions show large differences among different regions. In some regions abundant water availability provides ample opportunities for energy crop production, while water scarcity in other regions is seriously restricting any opportunity for energy crops.

To determine water availability for energy crop production a basin scale seems most appropriate in order to assure that the interaction between upstream and downstream water availability and use is taken care of. A suggestion is to execute the following steps:

- Estimate renewable water resources on the scale of a “river basin” area.
- Determine how much water is required for food and feed crop production related to local production systems and regional developments and estimate future projections.
- Estimate the environmental water requirements.
- Verify the available land area for additional (energy) crop production.
- Assess the regional and crop(type) specific water use efficiency of the energy crops to be cultivated.
- Assess whether water availability or land area is a limiting factor for bioenergy production for different parts of the river basin.

This procedure favors a multi-scale approach taking into account the influence of local measures on the larger regional scale and vice versa. It does not require just straightforward aggregation but a more detailed analysis of relations to arrive at an optimal water distribution. The local situation should be analyzed to assess the scope for energy production. However, to date, studies at this resolution have only been done

incidentally, and global figures give a misleading picture.

A rough estimate of available blue water for energy crops, based on global water flows, is 1,300–5,000 km³, depending on the share required for EWR (50–20%). However, where this water is available and if it can really be used cannot be determined based on available studies. Future change in rainfall patterns will regionally have a large impact, especially in regions that are already water scarce.

Food

Technologically speaking, producing enough food for even ten billion people seems feasible [38]. In contrast, doing so without compromising sustainability – both by pollution and by resource depletion – will be a formidable challenge [39]. Currently, food production appropriates about 75% of the available freshwater and 35% of the global land area [40]. While the world population doubled during the second half of the twentieth century, in consequence of increasing incomes, its appetite for meat quadrupled, requiring 40–50% of the world grain harvest to be fed to livestock [38]. Within the food domain, meat production has a disproportionate environmental impact [41] and, therefore, environmental impacts of food production are strongly coupled to actual diets.

The key metric with regard to food demand is elusive. For example, in the Netherlands the food consumption is about 20% lower than the food production [42]. This difference can only be approximated, since the quality of FAO food supply data is poor. Furthermore, food prices are hard to predict.

The ideal study estimating food demand takes at least into consideration (1) world population, (2) economic aspects (including income and food prices), (3) production systems, and (4) diet characterization, in sufficient geographic and temporal detail.

The principal food demand projections [43] address world population growth, diet changes (increased use of animal products), yield increases (including those due to use of GMOs), and economic aspects. Freshwater resources are taken into account, but biofuel production is not addressed. Projections are at a general, aggregate level and quite optimistic with regard to yield increases and the effects of climate

change. In general, these studies seem to implicitly and explicitly favor further intensification of agriculture, without paying much attention to the potential of organic production.

The real drawbacks of FAO data [43] are that it regards supply (production + imports - exports) per country, per commodity. That is not a very firm basis and, furthermore, everything after primary production, such as food processing, transport, refrigeration, etc., is lacking, and so is innovation in the latter part of the chain.

Primary production systems underlying FAO projections are described in sufficient detail. The majority of farming systems are small-scale operations, particularly in developing countries. Although an inventory of such production systems has been made available by the FAO and the World Bank [44], detailed projections of their development and future contributions to world food production are lacking altogether. The direction and rate of innovation of primary production is taken into account in the FAO projections, but evidently hard to model. Furthermore, availability of food is interrelated to other products, such as feed, fuel, and materials derived from crops and livestock, in a very complex way.

In striving for sustainable food production and consumption, the protein chain is an excellent starting point [45–47], as on average, 6 kg of plant protein is required to yield 1 kg of meat protein [48, 49]. In theory, a promising solution may be offered by partial replacement of meat proteins with plant protein products (so-called Novel Protein Foods, NPFs) in the human diet. It is estimated, conservatively, that – without putting a healthy nutrition in jeopardy – world meat supply could easily be cut by *one third*, that is, from 140% to 166% to 100%. Even then, the average protein consumption would be 20% over the RDI (recommended daily intake) and one third of protein consumption would still be derived from meat. Life cycle assessment showed that a partial transition from animal to plant protein (abolishing feed production but keeping extensive livestock, i.e., feeding on grass and agricultural waste) might result in a three- to fourfold lower requirement of agricultural land and freshwater to start with. Moreover, worldwide there is potential for a 30–40-fold reduction in water use [41]. Several economic arguments [50, 51] indicate,

however, that actual practice may not be as straightforward as theory suggests, due to status and cultural trends.

The principal food demand projections are those by the FAO, which are based on supply (production + imports - exports) per country, per commodity. They are the best available, but the descriptive data is crude and so are the projections based on them. The largest knowledge gap in the available models and data is probably in consumer preferences. Studies of diet change show that in addition to availability and price, status aspects and cultural trends play an important role.

Biomass Demand for Energy

In order to put the assessment of biomass potentials and their interrelations with other land-claiming functions into perspective, an assessment is also made of future energy demand development and the foreseen role of biomass therein. (Note that almost all of these demand-side models also need to make assumptions on availability and cost of biomass, in order to compare competitiveness of biomass and other supply options. As such, it is not possible to make a clear-cut distinction between biomass supply and biomass demand assessments.)

Earlier demand projections for primary biomass for production of transportation fuel were largely based on the World Energy Outlook (WEO) of the International Energy Agency of 2006 [52], with a relatively wide range of about 14–40 EJ of primary biomass, or 8–25 EJ of fuel. However, higher estimates were also included, ranging between 45 and 85 EJ demand for primary biomass in 2030 (or roughly 30–50 EJ of fuel).

Demand for biomass for heat and power was stated to be strongly influenced by (availability and introduction of) competing technologies such as CCS, nuclear power, wind energy, solar heating, etc. The projected demand in 2030 for biomass would be around 28–43 EJ according to the data used in the 2007 IPCC report [2]. These estimates focus on electricity generation. Heat is not explicitly modeled or estimated in the World Energy Outlook, therefore underestimating total demand for biomass.

Also potential future demand for biomass in industry (especially new uses as biochemicals, and also

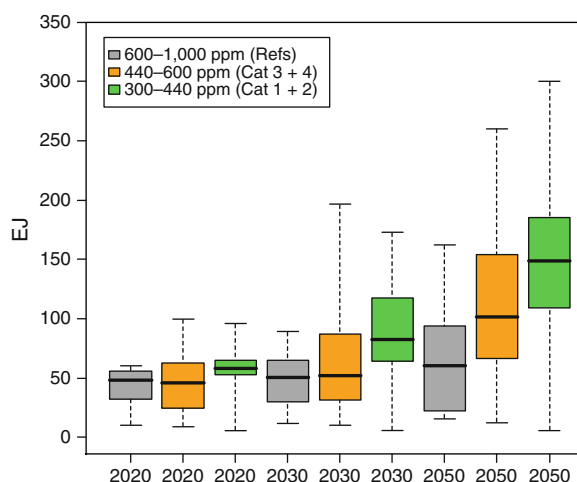
expansion of charcoal use for steel production) and the built environment (heating as well as increased use of biomass as building material) was highlighted as important, but no quantitative projections were included in potential demand for biomass on medium and longer term.

The results of the review of studies with respect to bioenergy deployment under different scenarios as presented in the scenario study review of the IPCC Special Report on Renewable Energy [53] are summarized in Figs. 4 and 5. For medium term (2030), estimates for primary biomass use range (rounded) between 7 and 180 EJ for the full range of results obtained. The 25–75% quantiles deliver a range of 30–117 EJ. This is combined with a total final energy delivered of 0–61 EJ. For 2050, these ranges amount for primary biomass supplies 10–305 EJ for the full range and 22–184 EJ for the 25–75% quantiles and 0–76 EJ (22–57 EJ for the 25–75% quantiles) for the final energy delivered.

A first striking finding from this review is that the overall conversion efficiency from primary energy to final energy delivered appears to be 25% on average in 2050. Final energy is not defined in those aggregate results and a breakdown of biomass use for power, heat, fuels, and materials is not available. Given that the technology portfolio on medium and longer term allows for conversion efficiencies of over 90% for CHP and over 60% for production of some biofuels, the final energy delivered seems therefore grossly underestimated in the scenario range considered.

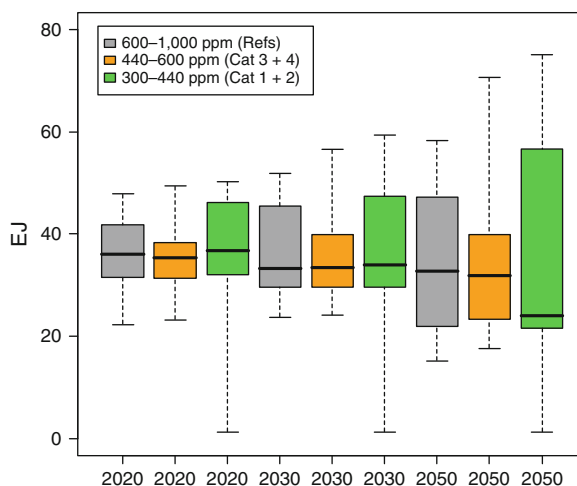
In the reference scenario of the WEO 2009 of the IEA [1], biomass is expected to contribute 66 EJ in 2030 (compared to 48 EJ in 2007). This includes traditional biomass use. Biofuels contribute 5% of world road transport energy demand; this is an almost fourfold increase compared to current production. Biomass for power increases from 259 TWh in 2007 (about 1 EJ_e) to 839 TWh (about 3 EJ_e) in 2030, mostly from CHP, as well as co-firing.

In the 450 ppm scenario, the contribution of biomass is projected to be 81 EJ, a 22% difference compared to the reference scenario. In addition it should be noted that in this scenario a decreased contribution of traditional biomass is assumed and the relative increase of modern bioenergy is larger than the 22% compared to modern biomass use in the reference scenario. Use of



Biomass Resources, Worldwide. Figure 4

The primary biomass utilization according to the scenario review the IPCC SRREN report, divided into projections for reference scenarios, scenarios that target 440–600 ppm, and scenarios that target 330–440 ppm. The *colored bars* represent the 25–75% quantiles of the obtained results. The *dotted bars* represent the full range of estimates



Biomass Resources, Worldwide. Figure 5

The final energy delivered via biomass utilization according to the scenario review of the IPCC SRREN report, divided into projections for reference scenarios, scenarios that target 440–600 ppm, and scenario's that target 330–440 ppm. The *colored bars* represent the 25–75% quantiles of the obtained results. The *dotted bars* represent the full range of estimates

biomass in CHP and electricity only increases by 67% compared to the reference scenario. Biofuel production is more than doubled compared to the reference scenario.

This is also confirmed by the results of the IEA Energy Technology Perspectives study of 2008 [54]. The analysis on biofuels projects a rapid penetration of second-generation biofuels after 2010 and an almost complete phase out of cereal- and corn-based ethanol production and oilseed-based biodiesel after 2030. This was a sharp contrast to the World Energy Outlook studies of 2006 and 2007 [52, 55], where second-generation biofuels were excluded from the scenario analysis and thus biofuels at large played a marginal role in the projections for 2030. This is a clear example of the importance of high quality data on performance prospects (and thus learning potential and rates) of energy technologies and in general for such strategic studies.

Agricultural Economics

Economics occupies a special position in the study, because it integrates costs and values. Ideally, it shows “what the society wants.” An ideal economic study on food and bioenergy production takes into account the effects bioenergy use on prices, production, and markets of all other crops. It compares the net-return of all possible crops which a farmer can grow. The competition with other markets (food, feed) – determining the output prices of competing markets and crops – is decisive for the economic feasibility of biofuels. The ideal study is able to deal with the interaction between the agro markets worldwide. This is essential due to the fact that (a) bioenergy can be produced using by-products and (b) the production of bioenergy often leads to by-products. Moreover, the ideal study is able to deal with the competing claims of food, feed, and fuel on production factors in order to estimate a real economic feasible production of biomass for fuel.

Agro-economic models that use the agro-economic principles described above have especially covered the possible price impacts of deployment of biofuels produced from food crops, simply because the current CGE models are equipped for that. To date, no full macroeconomic (scenario) analysis exists that

includes large-scale use of lignocellulosic resources, second-generation biofuels, power, heat, and (advanced) biomaterials. Therefore, no overall overview of consequences and no overview of economic feasible production can be given yet. Furthermore, the economic studies which have been done yet focus on first-generation biofuels. The second-generation biofuels and the use of by-products is the second step in the economic models and not implemented yet.

From the other studies found in the literature (i.e., based on the POLYSYS model from the University of Tennessee, the AGLINK model of the OECD, the Ethanol model from Iowa State University) it is clear that the discussions about the fuel sources need to take into consideration impacts on the world agricultural markets.

The driving forces behind agro-production are: demography, global change, political administrative regime, macroeconomics, agro-technology, and changes in value in society, consumer concerns, and behavior. In studies conducted by the FAPRI, OECD, and EU the link with the most relevant data sources (FAO, OECD, and EUROSTAT) have been made [56, 57]. It should be noted that those driving forces are influenced by many dynamic developments worldwide. This requires scenario analyses as is used in most economic studies.

The agro-economic studies that have been carried out often deal with agricultural land and do not take into account forestry land. They also do not deal with second-generation biofuels. The studies carried out illustrate the necessity of including competition and interactions between agricultural markets. The production of biofuels affects prices of feed and food. Those effects have to be taken into account in order to present a realistic picture of available biomass for biofuel. These effects are also relevant to assess the social sustainability of bioenergy, especially the effects on regional incomes and food security.

Methods used to estimate the global land-use impacts of bioenergy utilization are under continuous development to address discovered weaknesses. Field measurements and model validation are needed to reduce uncertainties of analyses and models [58]. Existing methods for determining ILUC (often grouped with LUC) can be divided into two methods employing macroeconomic/econometric and/or

biophysical models and deterministic methods allocating global land-use change to respective fuels/feedstocks grown in a few specified land types [59]. If specified land types were altered or key types absent, different carbon stock values (above and below ground) would be obtained over time [60]. Various studies use a combination of macroeconomic/econometric models and/or biophysical models/data. Some government studies implement policies to encourage the increased use of biofuels that can be shown to achieve GHG reductions as measured through direct and indirect impacts. One case uses absolute values of carbon intensity (CARB) while others set GHG emissions reductions thresholds relative to fossil fuels.

Implementation of the use of these modeling systems generally proceeds in two phases. Global land-use change as derived from scenarios with and without policy-induced increases in bioenergy use is calculated. Then the impacts of ILUC are attributed to the appropriate fuel/feedstock as linked to via the economic system. Macroeconomic/econometric models combined with biophysical models/data are complex and resource intensive; they can be viewed as lacking transparency to non-modelers. Two studies utilizing these methodologies have conducted significant uncertainty analysis [61, 62].

The recently released EPA results (2010) resulted from a series of peer reviews and comments on initial modeling data (a similar review process is underway with CARB for ILUC determinations) [63]. Among improvements EPA updated the Brazilian land-use data, considering information provided by the Brazilian Land Use Model [64] combining remote sensing data, field data, and micro-regional modeling for inputs into a partial equilibrium model (FAPRI). With this inclusion, changes in the elasticities of multiple crops across several land types were obtained for a series of larger regions for a more detailed picture of the dynamics of land use within Brazil. The major land-use change has been pasture intensification with use of degraded pastureland for biofuels derived from soya and sugarcane; also occurring are crop substitutions in the Cerrado and other regions [64]. Earlier modeling exploring the land-use consequences of increased use of US corn for ethanol production used lower spatial resolution and did not include pastureland among land types covered, resulting in the conversion of forests to

cropland for food and fuel production [65]. LUC estimates vary depending on model and scenario assumptions. Corn LUC results are converging with improvements in the models and their input data. Initial dynamic results are shown in EPA's results.

This method assumes that additional biomass production will inherently lead to an increase in land-use change, perform a calculation of total LUC impact using census/spatial data/measurements, and then allocate ILUC impacts among energy feedstocks/fuels. ILUC can be divided over a period and converted to various functional units to determine the impact of a feedstock or fuel on ILUC. Example approaches are reported in [66, 67]. The benefits of these deterministic methods are that they are simpler and more transparent to potential users. These methods are less resource intensive, but the simplified methodology might lead to the loss of important details of geographic scope and currently lack dynamic capabilities.

The assessment of available literature showed that initial models were lacking in geographic resolution leading to higher proportions of assignments of land use to deforestation than necessary as the models did not have other kinds of lands such as pastures in Brazil that could be used. First an ILUC factor of 1 (losing 1 ha of forest land for each hectare of land used for bioenergy) has been claimed [65]. Later macroeconomics coupled to biophysical model studies tuned that down to 0.3–0.15 and more detailed evaluations (e.g., [68, 69]) suggest that any ILUC effect strongly (up to fully) depends on the rate of improvement in agricultural and livestock management and the rate of deployment of bioenergy production. This balance in development is also the basis for the recent European biomass resource potential analysis, for which expected gradual productivity increments in agriculture are the basis for possible land availability [70, 71] and that take avoidance of competition with food (or nature) as a starting point. Increased model sophistication to adapt to the complex type of analysis required and improved data on the actual dynamics of land distribution in the major biofuel-producing countries is now producing results that are converging to lower overall land-use change impacts and acknowledgement that land-use management at large is key.

Integration of the Findings

In the first part of this entry, existing literature on bioenergy potentials and consequences of bioenergy use for issues such as biodiversity, food prices, and water use were assessed. This assessment not only provided information on these issues, but also showed key uncertainties. Many of these uncertainties originate from the fact that existing studies have only partly dealt with the linkages between bioenergy use and other issues. For instance, none of the studies on potential for bioenergy considered potential impacts on water use.

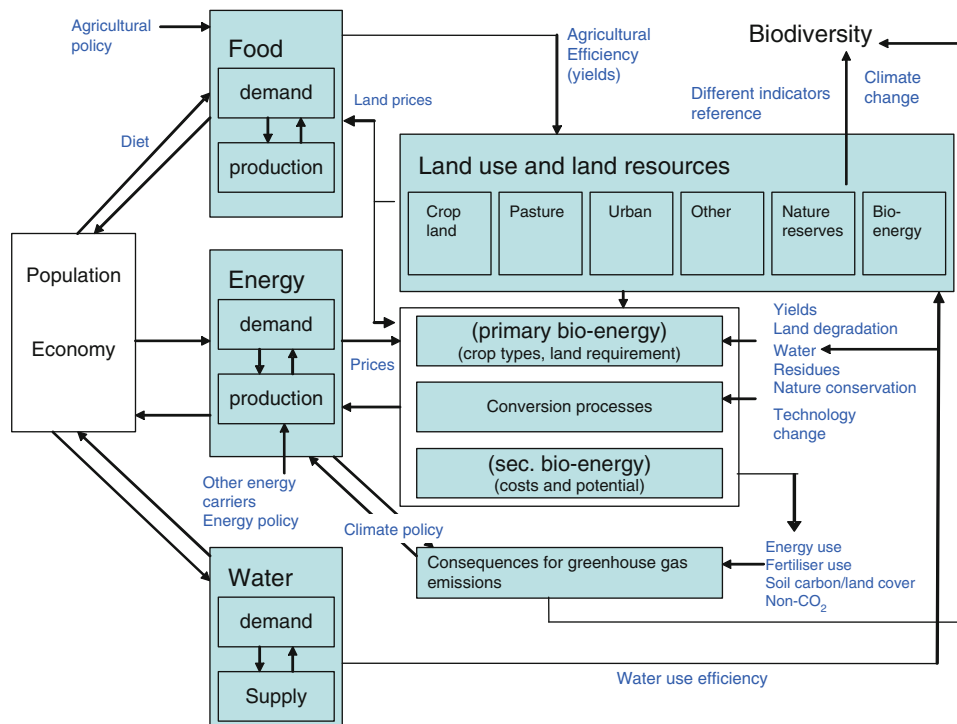
An important reason for the conclusion that studies mostly look only at a part of the relevant issues is that the relationships between these issues are complex and therefore cannot be captured in detail by a single study or model. In this context, Fig. 6 highlights some of the key relationships and

assumptions that could determine an overall assessment of bioenergy (in blue).

In this entry, some insights are provided into the impacts of more integrated considerations by performing some sensitivity analysis using existing models. The aim of these analyses is not to provide quantitative answers, but instead to assess the possible impacts of some key uncertainties (selected on the basis that they could be analyzed within the scope of this assessment).

The analysis concentrates on the following main issues:

1. The role of bioenergy use in energy models; in particular to identify which factors can limit penetration of bioenergy (potential for bioenergy, long-term cost-supply curve, energy use in specific sectors); and the sensitivity of bioenergy potential estimates to issues such as uncertain development



Biomass Resources, Worldwide. Figure 6

Overview of some key relationships and assumptions relevant to assess potential bioenergy supply. The figure is only meant as an indication (e.g., other relationships also exist and scientific disciplines may order to information differently) [25]

- of agriculture technologies, land use, water scarcity, land degradation, and nature reserves
2. Key uncertainties in assessing biodiversity losses as a result of land conversion for bioenergy
 3. The economic link between food, feed, and fuel

Impacts of Key Uncertainties

In the inventory part, it has been looked into various estimates for potentials for bioenergy – one of them by Hoogwijk [4, 13]. Compared to others the estimates of Hoogwijk are relatively elaborate – but do not consider issues such as water scarcity or greenhouse gas impacts. In that context, the methodology of Hoogwijk is implied but some sensitivity analysis to estimate the potential impacts of alternative assumptions are included.

Hoogwijk's method is indicated in Fig. 7. First, suitable areas for bioenergy are identified on the basis of land-use scenarios that do not include bioenergy. In the calculations all areas required for food production are excluded. On the remaining areas (1) a land-specific exclusion factor (between 0% and 100%), (2) the rain-fed potential energy crop productivity (depending on crop, soil, and climate), and (3) the assumed state of agricultural management (% of potential production) determine the potential. In the calculation presented here, the exclusion factor for forests and nature reserves is 100%, and 50% for natural grassland ecosystems (e.g., steppe, savannah, and grasslands). The total potential is equal to the sum of all areas.

The potential for bioenergy determined thus concentrates on two areas:

- Abandoned agriculture land (in the short term mainly in developed regions; but later on also in some developing regions)
- Natural grass ecosystems (an exclusion factor of 50% is used here, leading to an expansion of total arable area, but outside forest)

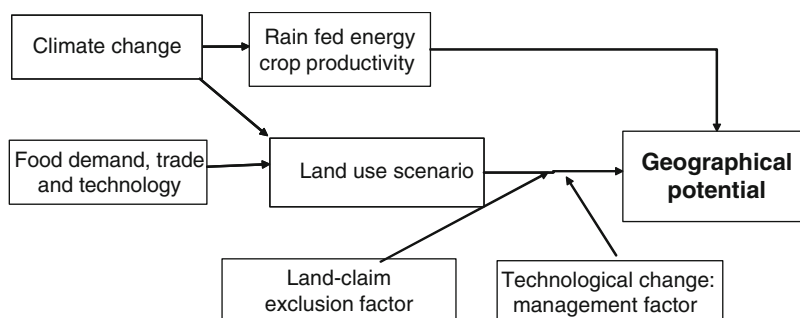
Finally, also areas with a very low potential yield (part of tundra and desert ecosystems) are excluded.

Below, the Hoogwijk method is applied and the following uncertainties are analyzed:

- Different scenarios
- Different crops and land areas
- Water scarcity
- Land degradation
- Nature reserves

Many global land-use scenarios show potential land abandonment in parts of the world (e.g., the Millennium Ecosystem Assessment, several scenarios assessed in the recent IPCC AR4 report, the IPCC SRES scenarios). Nevertheless, from an economic perspective this feature is sometimes questioned as lower land prices would slow down the incentive for agricultural yield improvement. The scenario taken here as central case does have the feature of land abandonment.

Finally, in Hoogwijk's original application nature reserves existing in 2000 were excluded from potential biomass production. Here, to explicitly analyze the influence of biodiversity restrictions this assumption has only been added in the discussion on nature reserves.



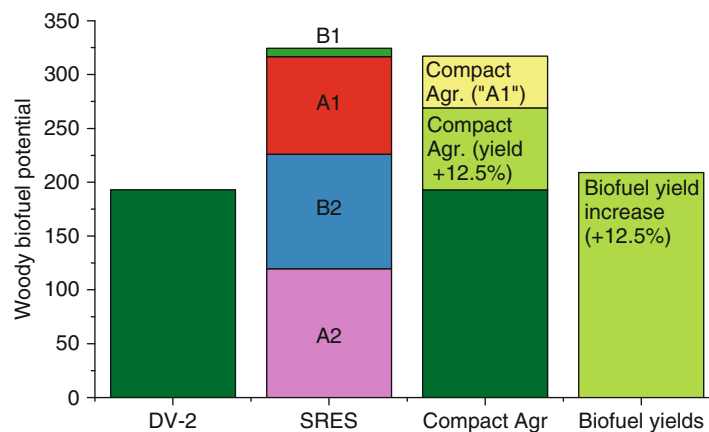
Biomass Resources, Worldwide. Figure 7
Methodology of assessing bioenergy potentials

Different Scenarios The analysis of Hoogwijk concentrated on the geographic and economic potential of woody biofuels – using the IMAGE implementation of the IPCC SRES scenarios as a basis. Given new insights into possible future changes, here instead the reference scenario of the Netherlands Sustainability Outlook and the OECD Environmental Outlook (DV-2 or OECD baseline) [57] is used. (The reference scenario of the DV-2 is based on work that has been performed jointly by the OECD and MNP, and also forms the reference scenario of the OECD Environmental Outlook [57].) This scenario should be regarded as a “medium-development” type of scenario (in terms of population and economic change, but also agricultural productivity change). GDP per capita grows globally by about 2% per year, while the global population reaches a level of 9.4 billion people in 2050. Changes in agricultural yield and consumption patterns are based on the FAO projections [72]. The resulting agricultural land worldwide (including extensive grassland) increases from 4.9 Gha in 2000 to 5.5 Gha in 2050 (excluding extensive grassland; these numbers are 3.8 and 4.4 Gha). The extension of agriculture land occurs almost exclusively in developing countries, while land use in OECD countries remains more or less stable. Compared to the IPCC scenarios, in terms of most assumptions, the scenario lies in between the A1b (high economic growth) and B2 (medium assumptions) scenarios. Scenario-related assumptions (such as for population growth, food demand, agricultural trade, and

technology change [6, 13]) are very important for the potential for bioenergy.

The potential as calculated using the methodology indicated in Fig. 8 on the basis of the OECD-baseline scenario in 2050 is around 200 EJ. (In other words, the total area of abandoned agricultural area and natural grass ecosystems, taking into account the 50% exclusion factor, could produce 200 EJ of primary bioenergy). Using the land-use patterns of the IPCC SRES scenarios (but keeping other factors, such as assumed bioenergy yields and land-claim exclusion factors the same as under the OECD-baseline scenario) would lead a range from 120 to over 325 EJ (with low potentials in A2 as a result of a high population growth, low yields, and little trade; and high potentials in A1 and B1 as a result of low population growth and rapid yield change).

An important factor in these calculations is the assumed changes in yields. This is also shown in Fig. 8 by indicating the two alternative cases that look into a more compact agriculture compared to the OECD-baseline (DV-2) scenario (and thus higher yields). In the first, agricultural yields are improved for all crops and regions by 12.5% compared to the base case. The value of an additional increase of 12.5% is equal to half the suggested improvement potential compared to baseline in the International Assessment of Agriculture Science and Technology Development (IAASTD). The second scenario of more compact agriculture applies the same convergence in agriculture



Biomass Resources, Worldwide. Figure 8

Potential for primary woody bioenergy (not including residues) and using different scenario assumptions

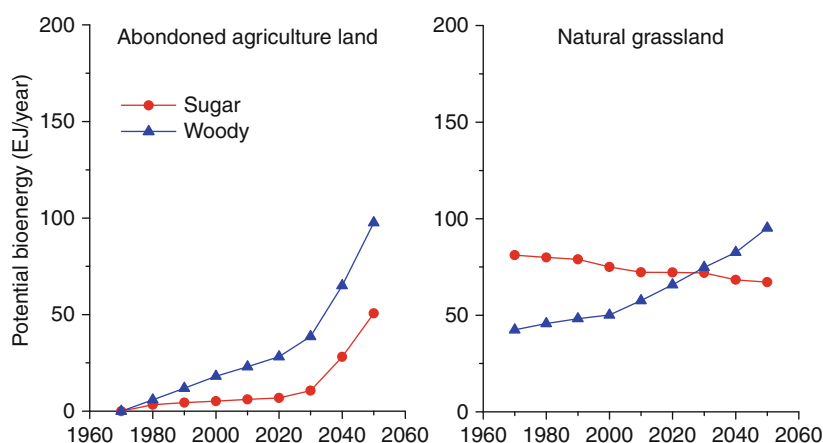
yields worldwide as in the A1 scenario, that is, bringing 2050 technology levels in developing countries close to current Western European levels – while keeping the baseline improvement for developed countries. Both cases lead to a considerable increase in potential compared to the OECD-baseline scenario: 40% for the first case and about 65% for the second. In other words, assumed yield changes for agriculture in general critically determine the potential for bioenergy. Assuming a more compact agriculture could possibly lead to about 300 EJ of primary woody bioenergy in 2050. It should be noted, however, that yield improvement could obviously also be slower than our base case assumptions. Furthermore, these calculations are single-factor variations: the changes in yields discussed here are likely to impact land and food prices, and could therefore lead to indirect effects.

Obviously, the yield increases for biofuel crops also are uncertain. The assumed increase in the base case is based on yield estimates by [13] and strongly varies per region (as 2000 yields are very different for different regions). Globally, these values lead to a 100% improvement for woody biofuels (assuming a low 2000 starting value). Assuming an additional improvement in yields of 12.5% (now without improving the yields of other crops above the baseline) leads to an increase of total potential compared to the

OECD-baseline scenario by 12.5%. This implies that in general the yield increases for food crops have a stronger impact on bioenergy potentials than the yield increases for bioenergy crops specifically.

Different Crops and Land Areas In addition to woody bioenergy, also other crops are already applied as feedstock for bioenergy. Woody bioenergy can be applied as feedstock into electricity and heat power plants and as feedstock for biofuels. Other, more conventional agriculture crops, such as sugar, maize, oil crops, and cereals, can also be converted into ethanol or biodiesel. Finally, agricultural residues also can be used.

Here, only the (primary) potential for woody crops and sugar is estimated, shown in Fig. 9 on both abandoned agriculture land and natural grassland. The potential on abandoned agriculture land increases over time – with more abandoned land becoming available. The potential on natural grassland is mainly a function of yields as the area of natural grassland is more constant. Worldwide, the potential for woody and sugar bioenergy is considerable. Sugar has very high yields in developing regions. The type of fuel chosen does obviously depend strongly on relative prices of crops, animal feed and food. In most cases, woody biofuel seem to become the most dominant feedstock worldwide of the two options evaluated here.



Biomass Resources, Worldwide. Figure 9

Potential for primary bioenergy on different crops and land types in the OECD-baseline (DV-2) scenario (potential cannot be added, as the same grid cell might be used for both the sugar and woody bioenergy potential). Natural grassland comprises natural ecosystems that would be converted into agricultural land [24]

Water Scarcity All calculations on bioenergy potential have been carried out assuming rain-fed production conditions. This can be regarded as an underestimation given the fact that irrigation could increase yields. However, IMAGE calculations do not take into account that other sectors than agriculture may also use (the same) water resources. In order to assess the potential impact of water scarcity on bioenergy potentials, here a map of the water stress indicator is used as calculated by the University of Kassel using the WaterGap model [34] on the basis of the same scenario as used for the bioenergy calculations (thus based on the same socioeconomic, land-use, and energy scenario). The water stress indicator is defined as the total actual water withdrawals as proportion of the maximum available runoff minus environmental water requirements. Values of this index of 0.2 and higher is defined as modest water scarcity, while values above 0.4 are defined as severe water scarcity [37]. Some authors have earlier tried to assess the impacts of water scarcity on bioenergy potential, showing that while impacts are not dramatic on a global scale, on a more local scale water scarcity may clearly limit bioenergy potential.

To assess the possible impact, here a simple overlay is made between the bioenergy map with the water stress indicator maps of the WaterGap model. This overlay suggests that about 15% of the total potential for bioenergy is in severe water-scarce areas (and might therefore be excluded), and another additional 5% in modest water scarcity areas (Figs. 10 and 11). It should be noted that to fully analyze the potential impacts of bioenergy on water scarcity, a better approach would be to calculate the water demand of potential bioenergy areas (using the water demand factors discussed in the integration analysis) and evaluate the impact of increased water demand at grid or watershed level.

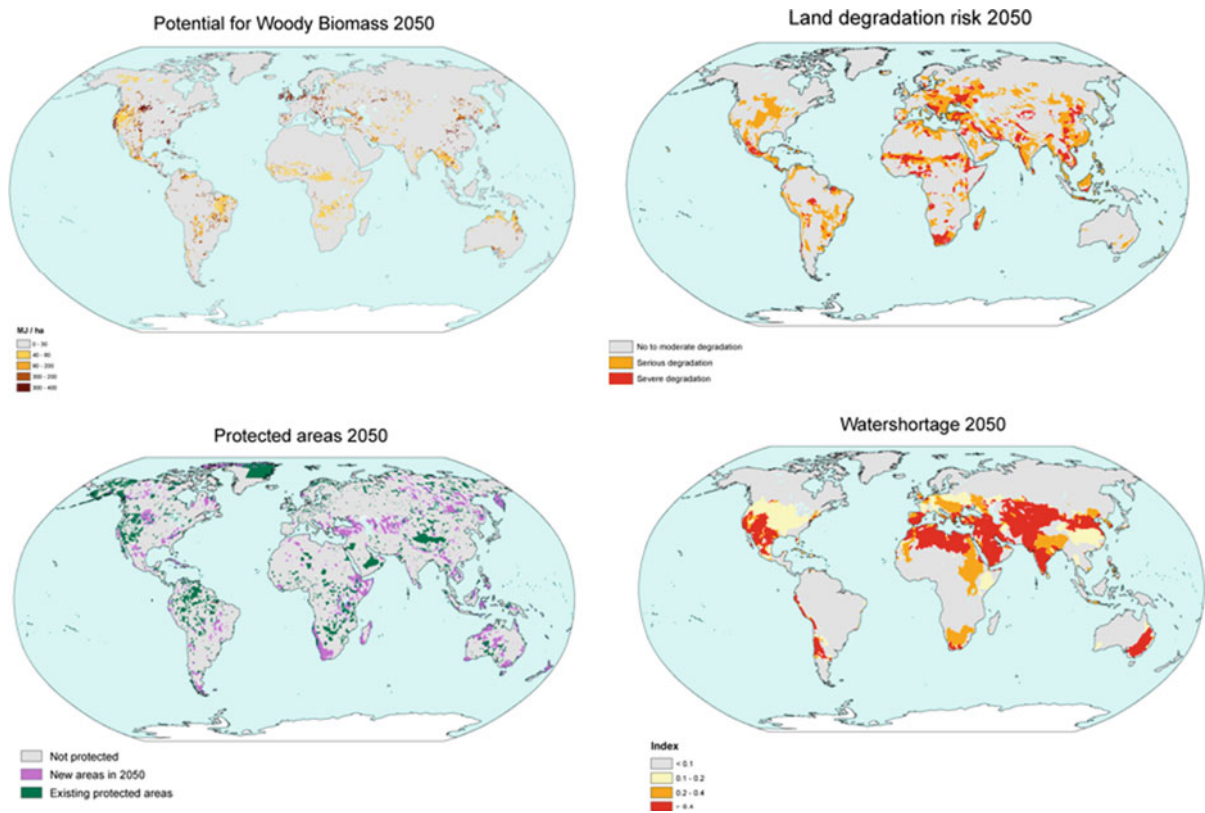
Land Degradation Degraded areas form an important topic in the discussion on bioenergy for two reasons:

- First, while abandoned agriculture areas are mentioned as a source for land for bioenergy, some of these areas are likely to suffer from land degradation. In fact, dependent on the degree of the degradation the soil might lose its function for biomass

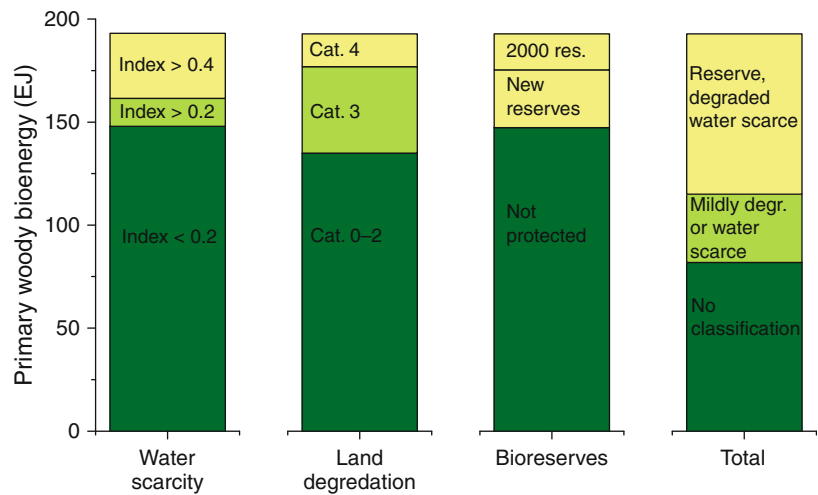
production or its function as substrate for natural vegetation. Reclamation of degraded soils into suitable land for production or into natural vegetation can be difficult.

- For less severely degraded areas, some people argue that by using these areas extensively (for bioenergy production), it is possible to enhance soil recovery. In this case, these areas would be prime expansion areas with little biodiversity impact as original vegetation cannot automatically recover. Whether this is actually possible needs to be looked into further, but using degraded land for production might need considerable inputs and investments, while it also might lead to benefits in view of recovery, biodiversity, and biomass production.

The IMAGE model does not model land degradation. In order to make a rough estimate of the impact of degraded land use on biomass potentials here, data from the GLASOD database have been used. The GLASOD database has classified land worldwide in terms of soil degradation. Two main criteria were used: the severity of degradation (category 1–4) and degree of degradation (0–100%). Next, these two axes for various degradation types have been combined into one final score again going from cat.1 to cat. 4. (Light degradation of soils means that there is a somewhat reduced productivity of the terrain and moderate degradation of soils requires major improvements often beyond the means of the local farmers. Strongly degraded soils are not reclaimable at farm level for food production and are virtually lost. Extremely degraded soils are considered irreclaimable and beyond restoration. The strongly and extremely degraded soils together cover about 300 million hectares. The total area of degraded soils is about 1964 million hectares, which is about 15% of the total land surface. The four main types of soil degradation, in order of importance, are water erosion (56%), wind erosion (38%), chemical deterioration (12%), and physical deterioration (4%). The degradation is in almost all cases human induced.) Using the GLASOD maps of soil degradation, three categories of degradation are distinguished: no-to-minor degradation (GLASOD cat. 1–2), serious degradation (GLASOD cat. 3), and severe degradation (GLASOD cat. 4). The last category is too severely degraded to include in bioenergy potentials because it



Biomass Resources, Worldwide. Figure 10
Maps of potential for woody bioenergy production in 2050, land degradation (map from the GLASOD database), protected areas (Sustainability First scenario GEOIV) and the water stress index (WaterGap results for 2050) as used in the analysis



Biomass Resources, Worldwide. Figure 11
Impacts of sensitivity analysis on 2050 potential for woody biofuels [24]

will not be feasible in practice due to high costs, while the second category could potentially include useful areas to target to combine soil restoration and bioenergy production. As much more analysis is required to assess whether such combination is possible, the overlay made here should be regarded as indicative. No assumptions have been made on lower yields and/or higher costs of exploitation.

The results show that biomass potentials would be about 8% higher in the OECD-baseline scenario (DV-2) if severely degraded land areas could be used. Another 22% could be gained in modestly degraded areas.

Nature Reserves Another important relationship exists between conservation of biodiversity and bioenergy use. It should be noted that already in all calculations so far, forest areas and 50% of natural grasslands (implemented for each grid cell) have excluded for reasons of biodiversity conservation. However, still bioenergy use could lead to a reduction of biodiversity (converting natural grass land to bioenergy crop area for instance). In order to provide some insight into the impact of further biodiversity restrictions on bioenergy potential, maps have been used of (1) nature reserves in the year 2000 and (2) areas designated to become nature reserves under the Sustainability First scenario of the Global Environmental Outlook of UNEP (it should be noted that in the original work of Hoogwijk and other IMAGE applications, nature reserves existing in 2000 are mostly already excluded from estimates on bioenergy potential). Under the Sustainability First scenario, most of the biodiversity hot spots are brought under protection – while the scenario also aims to protect sufficient areas of different eco-regions. Impact on bioenergy potential is considerable. Excluding reserve areas in 2000 reduces the total bioenergy potential by around 10% – while excluding the (very ambitious) expansion of reserves by 2050 would reduce the potential by another 15%. In total, this may lead to a reduction of bioenergy potential by 25%.

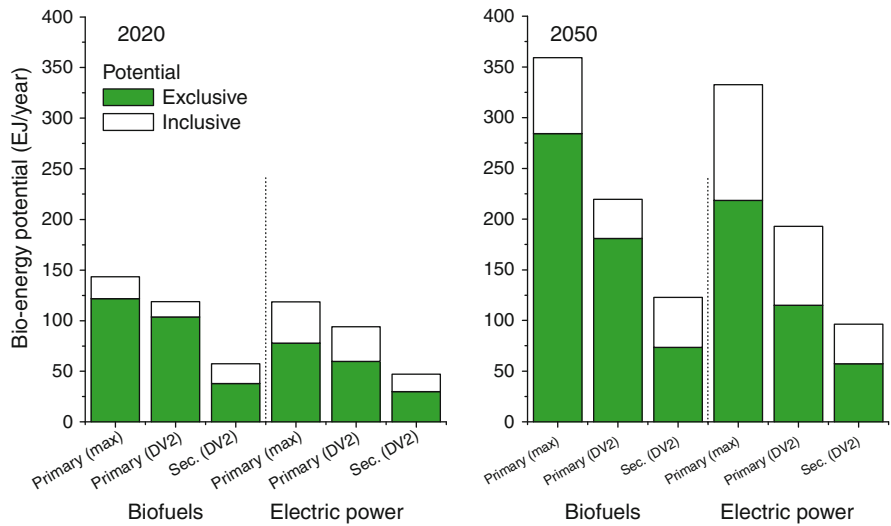
All Factors Together In Fig. 11, the combined impact of protected areas, degraded land, and water availability in sensitivity analysis (last column) is shown. As indicated, a considerable part of the original

potential either in severely water-scarce areas, in areas with severe land degradation, or in potential nature reserve areas. This part of the potential, that is, 40%, may be considered as not available. A second category is either found on soils with mild degradation or in areas with mild water stress. The question whether this part of the total potential (20%) can be used (or even maybe an attractive area to use, see soil degradation) remains open.

Figure 12 summarizes the findings of the analysis in a different way by showing the 2020 and 2050 total potential for biofuels and electric power using a crop mix that leads to maximal potentials for the production of biofuels or electric power. Results are given in terms of primary (before conversion) and secondary energy content after conversion: the actual energy produced in the form of biofuels or electric power. In each case, the first column indicates the most optimistic estimate for potential assessed here assuming the compact agriculture case and the 12.5% increase in yields for bioenergy crops. The second column shows the potential under the default OECD-baseline (DV-2) scenario case and finally the third column provides an indication of the potential after conversion. For each column, the white area indicates the part of the potential that might be excluded as it is either (1) severely degraded, (2) under severe water stress, or (3) potential nature reserve, while the green area indicates the remaining potential (for the individual impact of these factors see Fig. 11). The total potential for biofuels slightly exceeds that of electric power as here in some cases more productive crops are used (sugar; selection on lowest production costs).

For the OECD-baseline scenario, the remaining primary potential for bioenergy varies in 2020 somewhere around 70–100 EJ (for power and transport) and in 2050 somewhere around 100–175 EJ. Using more optimistic assumptions for development of agricultural yields, these numbers change into around 75–125 EJ in 2020 and around 200–275 EJ in 2050.

Obviously, the potential for bioenergy is pretty meaningless without an assessment of the associated production costs. On the basis of additional assumptions on capital and labor costs for production and conversion of bioenergy and transport costs, it is also possible to estimate the cost curves for both biofuels and (bio)electric power [4, 73]. The formula (a Cobb–Douglas production function) are here applied at the grid level – calculating production costs as a function of

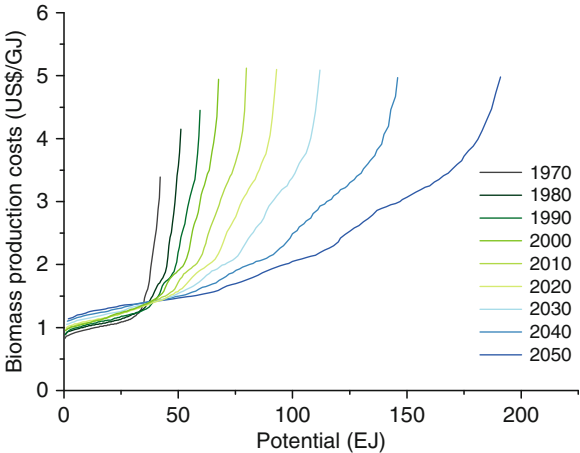


Biomass Resources, Worldwide. Figure 12
Potential for bioenergy, primary and secondary. Inclusive refers to the original estimates not accounting for restrictions discussed in the previous sections (i.e., soils with degradation or water stress). The exclusive potential does exclude severely degraded soils, areas under severe water stress, and nature reserves. The potential for secondary energy takes into account the conversion from primary energy into secondary energy carriers (fuels and electricity). Note that the potential for biofuels and electric power cannot be added as they refer to the same area [24]

GDP per capita (as proxy of labor costs), capital inputs, and yields [4]. Both yields and GDP are assumed to improve with time (consistent with the scenario discussed so far). The curves move out over time (as potential increases) and tend to move along the y-axis. The latter shows both an increase (as a result of labor costs increase) on the low side and a decline (as a result of technology progress on costs) on the high side. The curves assessed on the basis of the information presented here are shown in Fig. 13. It should be noted that adoption of bioenergy in the energy system will not be based on primary bioenergy costs (as calculated here) but on the basis of the costs of different fuel types. The cost of conversion is often more dominant in this.

Biodiversity Consequences

From a biodiversity point of view (as expressed in CBD and IPCC goals), the effects of growing bioenergy crops are the response to several (global) environmental developments. On the short term, land-use dynamics are dominant, while on the long term the contribution to reducing climate change becomes important.



Biomass Resources, Worldwide. Figure 13
Cost curves for biofuels following from the modeling based analysis [24]

Assessing both opposite effects of bioenergy is surrounded with considerable uncertainty, and is influenced by many other modeling exercises that are involved. For instance, projecting climate change will set the required mitigation efforts, while estimating

the biomass potential in mitigation will determine land use.

A complete sensitivity and uncertainty assessment should ideally consider: uncertainty in definitions (using different indicators), data uncertainty (land-use data), model parameter uncertainty (responses of climate change and other pressures), conceptual model uncertainty, and scenario assumptions. Only a few sources of uncertainty could be investigated, and are presented as first-order estimates of possible effects of scenario choices and model sensitivities.

The OECD scenario for the Environmental Outlook [57] serves as a background for this exercise. In the OECD-baseline scenario, biodiversity declines by 11% between 2000 and 2050 (expressed in MSA). For an ambitious 450 ppm option for climate change mitigation, large-scale bioenergy production is implemented with mainly woody biofuels. For this, 1.8 million square kilometers of abandoned agricultural land is used, and a further 3 million square kilometers of extensively used grasslands (considered having a seminatural character) are converted. Compared to the baseline, the total biodiversity decline in the option is 1% less (relative difference of 10%).

Local Biodiversity of Different Crops Important for the local biodiversity of production areas are the specific crop types used, and the type of land allocated for biofuel production. Three different hypothetical cases can be compared: using converted natural areas, using abandoned agricultural areas, or using agricultural areas. The resulting differences of several percentages at most are relevant compared to the complete 450 ppm option effect of $\pm 1\%$.

1. Growing bioenergy crops on natural areas (converted forests and natural grasslands) will lead to large biodiversity losses. Agricultural crops lead to a loss of -3.1% , woody biofuels to -2.7% , and agroforestry systems to -1.8% .
2. Using abandoned areas will lead to lower local biodiversity losses. Here it is assumed that these areas would otherwise be used for nature restoration (leading to partially recovered nature in 2050). Using these abandoned areas will then lead to losses of -1.3% for agricultural bioenergy crops, -0.9% for woody biofuels, and no net loss for agroforestry.

In the OECD climate change option, a large part of bioenergy production is allocated on extensively used seminatural grasslands. These grasslands may contain valuable biodiversity, as is the case for European High Nature Value farmlands (mostly grasslands) that are important for conserving agro-biodiversity. Temperate grasslands present a category that is underrepresented and falls short of the 10% target for global Protected Areas [74]. More knowledge on the global extent and biodiversity status of extensive grasslands and their attractiveness for biofuel production is needed to better assess this subject.

3. Agricultural areas contain a relatively low local (residual) biodiversity. Replacing these crops with woody biofuels leads to a local biodiversity increase of $+0.5\%$, and using mixed land-use systems (agroforestry) leads to an increase of $+1.4\%$. However, this local biodiversity effect neglects the possible shift in production area for food production. The total effects of land-use dynamics on a global level will therefore be different.

The mean MSA values for different land-use categories are sufficiently known for application in global land-use assessment, but there is considerable variation in values between individual studies. These can be the result of, for instance, different time scales (years after conversion), landscape structure, and specific management. A further analysis on these sources of variation can possibly give insights into (local) practices that are favorable for combining biodiversity and human use at local scales.

For these exercises, a constant area for bioenergy production is taken for comparative reasons. This leaves the specific contribution of crops to reducing atmospheric carbon out of consideration that will determine the required area for the different crops. Further, when agricultural and abandoned areas are used, shifts in food production regions can be expected and consequently further biodiversity losses. The exact effect of different crops and allocation can only be investigated by global and integral modeling exercises.

Uncertainty in the Climate Change Response Different model concepts and indicators may give different results for future effects of climate change on

biodiversity. For instance, the MSA indicator presents changes in local species abundance. Other often-used indicators focus on the risk of ultimate species extinction [75]. Different outcomes will not easily converge with more research, but must be seen as complementary information on the complexity of the biodiversity issue, and the mechanisms underlying biodiversity change.

The GLOBIO implementation of stable areas with suitable environmental conditions shows relatively little variation in the calculated parameters. More variation can be found in different climate models that give future environmental conditions, and in the sensitivity of the climate system to rising atmospheric CO₂-eq concentrations. With extreme values for climate sensitivity and assuming linear responses of biodiversity, a biodiversity response from -1.8% to -4.5% is estimated. This range in values is comparable to the values found for the different crop types and land allocation.

In integral models, several different global developments take place simultaneously. This makes it hard to exactly assess the effect of biofuels alone and the factors that may tip the balance between losses and gains. The bioenergy effects can be better assessed by implementing hypothetical scenarios, varying the implementation of biofuels only. Assuming linear responses between emission reductions and biodiversity effects, a first exercise shows that the total balance between land-use changes and climate change effects will probably be negative (total effect of -0.8% to -1.4%). In the 450 ppm options, the reduced climate change effects are the result of a complete package of mitigation measures, while woody biofuels are responsible for about a third of the effect.

Including Species Richness in the MSA Indicator

An important characteristic of the MSA approach is the integration of different impacts in one and the same indicator, and the possibility to aggregate the biodiversity values over countries and regions. This allows comparing and balancing different pressures and time scales. As a consequence of this approach, MSA is not sensitive to all aspects of biodiversity. It is not sensitive to the species richness of different biomes, and all different ecosystem types (whether species rich or poor) are treated equally.

To explore the possibilities of including species richness in the indicator, the weighing was complemented by species weighing. This was done by using species richness numbers compiled for each distinguished eco-region (64 in total [76]). The species weighted MSA accentuates species-rich regions, such as Latin America, Africa, and parts of Asia. The global biodiversity decline for the OECD baseline is now somewhat larger (-1%). However, the same happens in the 450 ppm option, and the net result hardly differs from the usual MSA.

Conclusions With the presented and discussed sources of uncertainties and assumptions, a limited range of sensitivities was presented for the IMAGE-GLOBIO approach for assessing biofuel effects.

Ultimately, the effects are determined by the balance between land-use changes and climate change effects. Specific used crop types and land-use dynamics exert an important influence on this net outcome. Using still natural areas obviously leads to the highest losses, while using abandoned lands might reduce this loss. Using agricultural areas gives the lowest local impacts, but neglects shifts to other food production regions. The most important scenario uncertainty lies in the assumptions on agricultural land use versus abandoned and converted land use. Biodiversity responses to climate change remains a subject for further investigation, but will undoubtedly give different results, depending on the models and concepts used.

The exact conditions under which abandoned areas will be available for biofuel production remain a matter of discussion. Trade and cost mechanisms usually determine the regional allocation of abandoned and natural areas. As such, land abandonment is independent from biofuel production, stimulated by liberalization and differences in regional production costs. But bioenergy production can also be considered as a stimulating factor through land competition.

Making a balance between global land-use changes and climate responses must be done by integral modeling, as the specific crop potentials determine the required area for biofuels and the contribution to reduced atmospheric CO₂ concentrations. Including both elements (land-use changes and CO₂ reduction) in one life-cycle-analysis type of indicator may prove useful to summarize the balance. A first estimation of

this net biofuel effects, separated from other scenario developments, indicates that the biodiversity loss through land-use change is larger than the reduced climate change effects, brought about by bioenergy production alone.

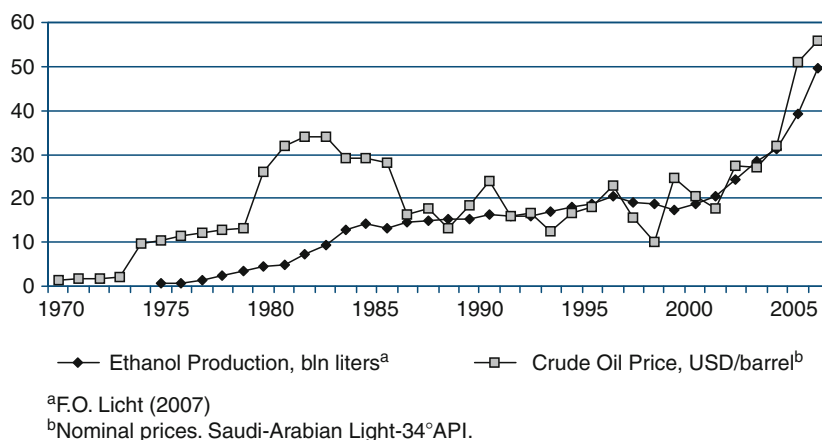
It can be concluded that for biodiversity considerable scientific uncertainty exists due to ongoing debate on methodologies on how to quantify biodiversity impacts in general. Clearly, large-scale monocultures that would go at the expense of nature areas are detrimental for biodiversity (e.g., highlighted in [30]). However, as discussed, bioenergy can also lead to positive effects such as the environmental benefits that can be derived from integrating different perennial grasses and woody crops into agricultural landscapes, including enhanced biodiversity, soil carbon increase and improved soil productivity, reduced shallow landslides and local “flash floods,” reduced wind and water erosion, and reduced volume of sediment and nutrients transported into river systems. Forest residue harvesting improves forest site conditions for replanting and thinning generally improves the growth and productivity of the remaining stand. Removal of biomass from over dense stands can reduce wildfire risk. Again, biomass production and its specific location, level of land-use planning and zoning, and effective environmental impact and management systems can lead to low-impact biomass production systems. This is also an area that deserves considerably more

research, data collection, and proper monitoring, as exemplified by ongoing activities of governments and roundtables in case or pilot studies [77–79].

The Economic Link Between Food, Feed, and Fuel

Worldwide production of biofuels is rapidly growing. Worldwide production of ethanol tripled from 20 billion liters to 50 billion liters (Fig. 14) and world biodiesel production has grown from 200 million gallons to almost 1,000 million gallons in the period 2001–2005. In the European Union in 2004, about 0.4% of the EU cereal and 0.8% of the EU sugar beet production was used for bio-ethanol, and more than 20% of oilseed production was processed into bio-diesel. The growth rate over the previous 2 years (2002–2004) was 27% and 70% for bio-ethanol and bio-diesel, respectively [81].

The production of biofuels started after the high oil prices in the 1970s which were due to supply restrictions by the OPEC cartel (Fig. 14). High oil prices induced innovations that saved oil or replaced oil by cheaper or more reliable substitutes, such as biofuels. World bio-ethanol production grew to about four billion gallons in 1985. In the early 1980s, the oil prices collapsed to their original level and stayed there until the beginning of the new millennium. The level of biofuel production, however, did not collapse but remained almost constant and increased only



Biomass Resources, Worldwide. Figure 14

World fuel ethanol production and crude oil prices: 1970–2005 [80]

marginally after 1985. The recent rise in oil prices in combination with environmental concerns lead to the recent biofuel boom.

The only integrated biofuel market in practice is Brazil's cane-based ethanol market. In their ethanol/electricity cogeneration system sugar cane becomes a competitive energy provider at petrol prices of about \$ 35/bbl [82]. The driver for biofuel production in the EU, the USA, and Canada is mainly political, including tax exemptions, investment subsidies, and obligatory blending of biofuels with fuels derived from mineral oil, while high energy prices further enhance biofuels production and consumption in other countries and regions. Arguments for biofuel promoting policies are reduction of greenhouse gas emissions in the light of climate change, diversification of sources of energy, improvement of energy security, and a decreased dependency on unstable oil suppliers, benefits to agriculture and rural areas, etc.

The growing integration of food and energy markets increases the ability to channel agricultural supply either to food, feed, or fuel processing. If this trend continues one can expect that the agricultural raw material price implied by future energy prices will either act as a ceiling – as long as it is profitable to use biofuel crops for energy production – or, if agricultural prices go above such threshold, demand for bio-based products for energy production will become negligible. This basic price transmission from energy to agricultural prices depends on various factors, which are (a) conversion technologies and costs, (b) carbon prices, (c) legislation, for example, mandatory blending obligations, and (d) economic incentives such as subsidies or tax exemptions.

Until now biofuels have been produced by processing agricultural crops using available technologies. These so-called first-generation biofuels can be used in low percentage blends with conventional fuels in most vehicles and can be distributed through existing infrastructure. Advanced conversion technologies are needed for the next generation of biofuels. This generation will use a wider range of biomass resources – agriculture, forestry, and waste materials – and promises to achieve higher reductions in greenhouse gas emissions and the costs of fuel production [24, 83].

Given the current policy developments and the availability of just first-generation biofuels, an increased biofuel production either due to “pure” market forces and/or “policy” might have significant impacts on agricultural markets, including world prices, production, trade flow, and land use. The fact that demand elasticities for energy are much higher compared to most food products also contributed to the strong dynamics agri-food market shows during recent years. Linkages between food and energy production include the competition for land, but also for other production inputs. The effect of an increasing supply of by-products of biofuel production such as oil cake and gluten feed also affect animal production for instance.

Liquid biofuel production creates additional demand for agricultural commodities, including food-stuffs that place additional pressure on natural resources such as land and water and thus raise food commodity prices. Biofuels from lignocellulosic biomass can reduce it but not eliminate competition. To the extent that domestic food markets are linked to international food markets, even countries that do not produce bioenergy will be affected by the higher prices.

The OECD-FAO Agricultural Outlook (2008) model [56] found that if biofuel production were to be frozen at 2007 levels, coarse grains prices would be 12% lower and vegetable oil prices 15% lower in 2017 compared to expected biofuels increases. World maize prices would be 26% higher under a scenario of continued biofuel expansion according to the then-existing national development plans [84]. They would be more than 70% higher under a drastic biofuel expansion scenario where biofuel demand is double compared to the first scenario (these scenarios are relative to a baseline of modest biofuel development where biofuel production remains constant at 2010 levels in most countries). World prices for wheat, sugar, and other crops would increase with greater biofuels production, but would be less than in the case of maize and oilseeds. IFPRI (2008) estimated that 30% of the weighted average increase of world cereal prices was attributable to biofuels between 2000 and 2007 [85]. The eventual impact of biofuels on prices will depend on the specific technology used, the strength of government mandates for biofuel use, the nature of trade policies that can

favor inefficient methods of biofuel production, and the level of oil prices.

The impact of higher prices on the welfare of the poor depends on whether the poor are net sellers of food (benefit from higher prices) or net buyers of food (harmed by higher prices). The poor are a heterogeneous group, with some being net sellers of food while others are net buyers. On balance, the evidence indicates that higher prices will adversely affect poverty and food security, even after taking account of the benefits of higher prices for farmers [86, 87]. A major study of FAO on the socioeconomic impacts of the expansion of liquid biofuels [88] indicates that poor urban consumers and poor net food buyers in rural areas are particularly at risk. The number of malnourished children would increase by 4.4–9.6 million under the two above-mentioned scenarios [84].

Higher food prices will have negative consequences for net food-importing developing countries. Especially for the low-income food-deficit countries, higher import prices can severely strain their balance of payments. Food exporting countries will benefit from higher prices, but the number of such countries is limited and they tend to be more developed (e.g., Thailand, Brazil, and Argentina).

A significant increase in the cultivation of crops for bioenergy implies a close coupling of the markets for energy and food [89]. As a result, food prices may become more closely linked to the dynamics of world energy markets. Political crises that affect energy markets would thus affect food prices. For around one billion people in the world who live in absolute poverty, this situation poses additional risks to food security.

Meeting the food demands of the world's growing population will require an increase in global food production of 70% by 2050 [90]. This FAO study also estimates that the increase in arable land between 2005/2007 and 2050 will be just 4%. Given this limited increase, there could be significant competition for the use of agricultural land because biomass production is land intensive. Increased biofuels production could also reduce water availability for food production (as more water is diverted to production of biofuel feedstock). Cash crops can represent an additional incomes source and do not necessarily compete with food crops, and may contribute to improving food

security [91]. However, there are instances of negative effects of cash crops on food security [91–93].

Growing demand for biofuels and the resulting rise in agricultural commodity prices can present an opportunity for promoting agricultural growth and rural development in developing countries. The development potential critically depends on whether it is economically sustainable without government subsidies. If long-term subsidies are required, there will be fewer government funds available for investment in a wide range of public goods that are essential for economic and social development, such as agricultural research, rural roads, and education. Even short-term subsidies need to be considered very carefully, as once subsidies are implemented they can be difficult to remove. Experience from Latin America shows that governments that utilize agricultural budgets for investment in public goods instead of subsidies experience faster growth, more rapid poverty alleviation, and less environmental degradation [94].

Bioenergy may reduce dependence on fossil fuel imports and increase energy supply security, although the benefits are not likely to be large [88]. Case studies for several Caribbean countries have been completed and indicate large potential benefits. Recent analyses of the use of indigenous resources implies that much of the expenditure on energy provision is retained locally and recirculated within the local/regional economy, but there are trade-offs to consider. For example, the increased use of biomass for electricity production and the corresponding increase in demand for some types of biomass (e.g., pellets) could cause distortions leading to the temporary lack of supply of biomass during periods of high demand. Households are particularly vulnerable in this regard.

The technology and institutions used for biofuels production will also be an important determinant of rural development outcomes. For example, private investors in some instances will look to the establishment of biofuel plantations to ensure security of supply. If plantations are established on nonproductive land without harming the environment, then there should be benefits to the economy. It is essential not to overlook the uses of land that is important to the poor. Governments need to establish clear criteria for determining marginal or productive land, and criteria must aim to protect vulnerable communities and

female farmers who may have less secure land rights [88]. Research in Tanzania suggests that an outgrower approach to producing biofuels is more pro-poor, due to the greater use of unskilled labor and accrual of land rents to smallholders in this system, compared with a more capital-intensive plantation approach [95].

Increased investment in rural areas will be crucial for making biofuels a positive development force. If governments rely exclusively on short-term farm-level supply response, the negative effects of higher food prices will predominate. If higher prices motivate greater investment in agriculture (e.g., rural roads and education, research and development) from public and private sectors, there is tremendous potential for sparking medium- and long-term rural development. As one example, proposed biofuel investments in Mozambique could increase annual economic growth by 0.6%-points and reduce the incidence of poverty by about 6%-points over a 12-year period [96].

The increased use of residues for some feedstocks – such as pellets or used cooking oil – requires careful analysis. While residues are presently inexpensive, as the market expands or as other uses are found, the price could change dramatically. For example, used cooking oil in Europe went from a waste product to a valuable commodity. One must also assess the long-term supply picture. For example, beetle-killed timber in British Columbia, Canada, is a large source material for pellet manufacture for the European market, but it is not clear for how long it will be available.

Social impacts from a large expansion of bioenergy are very complex and difficult to quantify. In general, bioenergy options have a much larger positive impact on job creation in rural areas than other energy sources. Also when conventional agriculture would rationalize to “free up land” for bioenergy, the total job impact and value added generated in rural regions increases when bioenergy production increases [97]. For many developing countries, the potential bioenergy has for generating employment and economic activity in rural regions is a key driver. In addition, expenditures on fossil fuel (imports) can be (strongly) reduced. However, whether such benefits end up with rural farmers depends largely on the way production chains are organized and how land use is governed. In case (too) rapid bioenergy deployment competes with food production, increases in food prices can be significant as

shown by many recent studies that focused on implications of rapid expansion of first-generation biofuels produced from food crops: impacts on food prices – and more in general on food security – may be significant, particularly for poor people. It is also acknowledged in many analyses that when such competition is avoided, and value chains are properly organized (e.g., with cooperatives with proper ownership structures and using agroforestry systems), farmers and local economies can be major beneficiaries of additional biomass production for energy (see, e.g., [95]).

The way bioenergy is developed, under what conditions, and with what options will have a profound influence on whether those impacts will largely be positive or negative (see, e.g., [78, 79] with examples of such scenarios for Argentina). Bioenergy has the opportunity to contribute to climate mitigation, energy security and diversity goals, and economic development in developed and developing countries alike but the effects of bioenergy on environmental sustainability may be positive or negative depending upon local conditions, how criteria are defined, how actual projects are designed and implemented, among many other factors.

Discussion of the Results

From a review of recent literature, several issues evolved that influence the amount of biomass that will be available for energy and materials. For some of these issues, ranges of biomass potentials had been analyzed by means of scenario analysis in the studies reviewed. Furthermore, an indicative analysis of some of these main issues and their linkage to bioenergy potentials has been carried out using several energy demand and economic models. The issues analyzed were those that are relatively easy to integrate (even though on a rough level).

- *Improvement agricultural management.* Yields for food and energy crops as well as animal production system are a key issue in determining technical biomass potentials. It has been shown (e.g., [6]) that, depending on different medium to highly efficient agricultural management systems, the potentials for bioenergy crops vary from 200 to 1,400 EJ/year. Modeling in IMAGE has shown that increasing yield levels of food and energy crops by

about 12.5% and bringing 2050 technology levels in developing countries close to current Western European levels leads to an increase of 40–60% of biomass potentials. For comparison, global average increase in cereal yields between 1961 and 1998 was about 2.2%/year (FAOSTAT). (Extrapolating this global average rate of learning until 2050 would lead to an increase by a factor 2.5, while probably learning rates in developed countries that already learned a large part historically would be lower than in developing countries for which a large learning potential still exists.) An important aspect of improving agricultural management is the rate of deployment of more efficient agricultural management practices in the developing countries, which itself depends on many factors that are often included in scenario analysis, such as socioeconomic developments, policies, resource endowment, infrastructure, power, etc.

- *Choice of crops.* As yields, agricultural inputs, and suitability of different types of climate and soil can be very different for different crops, the choice of energy crop is very important for overall biomass potentials. In this context, the developments in biofuels are crucial. Most recent studies assume the use of perennial lignocellulosic energy crops that can be used for heat and power applications, second-generation biofuels, but not for first-generation biofuels for which sugar, starch, and oilseed crops are required. Perennial lignocellulosic crops, such as herbaceous and woody crops, usually have higher total energy yields than annual starch, sugar, and oilseed crops. The amount of biofuel that can be gained from these annual crops via first-generation processes from 1 ha is typically lower than the amount of biofuel that can be gained from lignocellulosic crops via second-generation processes. However, once second-generation technologies become commercially available, lignocellulosic agricultural residues of annual starch, sugar, and oilseed crops can also be used for biofuel production. Another advantage of lignocellulosic crops is the fact that they are usually better suited to marginal lands (i.e., lands on which crop yields are very low) than annual crops. However, some of these marginal lands might not be suited to biomass production at all. It should be noted that some

perennial crops that are suited to the production of first-generation biofuels such as sugar cane and palm oil have rather high yields too.

- *Bioenergy demand versus supply.* Typically, supply and demand of biomass are investigated in separate models leading to estimates of geographical – what can be produced given land availability – and economic – what will be produced and used from an economic point of view – biomass potentials. Most studies on geographical biomass supply estimate only total amounts of available biomass, while some also analyze cost-supply curves of biomass. Dynamic adaptations of biomass supply to demand are, however, not considered in recent studies. Comparing scenario analysis of available biomass supplies with bioenergy demands shows that demands are typically lower than supply, even though the gap depends on the costs of biomass as well as on the assumption on global energy demand. The global demand for biomass for the use for energy as modeled with TIMER is about 15–20% of the possible supply. However, no result of integrated modeling supply and demand is available considering price effects. It should be noted that energy demand depends on cost-supply curves of biomass as well as learning in energy conversion.
- *Use of degraded land for biomass production.* An important question for the total biomass potentials and the availability of land is if and which degraded land areas can be used for biomass production. Most recent studies include agricultural land without explicitly defining whether and what type of degraded agricultural land has been included. For example, [13] uses “low-productive lands” which produce about 1–3% of the global potential for energy crops. Here the potential of using severely degraded land has been estimated to increase potentials by about 30–45% compared to not using severely degraded lands. This estimate has been made using soil quality and climate as a basis of yield estimates. However, it is unknown whether the assumed yields are realistic as it is difficult to assess the impact of soil degradation on the productivity of the soil. This depends on many local conditions. In general, one can conclude that yield levels on degraded soils are often far below the levels of the undisturbed soil. Another issue is the

potential value of degraded lands for biodiversity. This value depends on whether and during which timeframe this land restores itself to pristine nature. Restoration of the original vegetation on degraded soils has problems similar to biomass production since most of the original conditions of the soil have been changed (lower nutrient levels, lower water holding capacity). However, it has been shown that taking biodiversity recovery into account presents a factor to consider for the net option effect in terms of biodiversity.

- *Competition for water.* The use of water for biomass production (rain-fed as well as irrigated production) competes with other industrial, domestic, and agricultural uses. In general, the impacts of water availability on biomass potentials could be large as water use for industrial and domestic purposes as well as for agricultural food production is projected to increase strongly in the coming years. The evaluation of the potentials shows that water scarcity (as estimated in the WaterGAP model and not based on a river basin scale) decreases the area available for energy crops by 15–20% and decreases the estimated biomass potential by 15–25% compared to the DV-2 scenario. The increasing variability of rainfall due to climate change is expected to decrease the area further, while an increase in water use efficiency of agriculture and the use of perennial lignocellulosic crops (that might increase water retention in some areas) could increase the biomass potential based on water availability. However, the review of studies on water has shown that the demand and availability of water cannot be analyzed on an adequate scale to evaluate biomass potentials for regions with possible water scarcity. At least an analysis on a river basins scale is needed, but these data are not systematically available.
- *Learning in biomass conversion and competing technologies.* The comparison of costs and efficiencies of biomass options with other options for energy supply is important for the use of fossil or biomass technologies for energy supply. This performance of energy conversion technologies can be influenced by “technological learning,” and a cost-reducing effect that occurs more strongly in newer technologies, for example, hydrogen fuel cells or biomass conversion, than in more conventional

(fossil and renewable) technologies. The results discussed, which assume different rates of learning, show that shares of bioenergy could vary strongly, but, for example, in energy model run with overall faster learning rates for selected conversion technologies, the role of bio-based is affected [54, 98].

- *Protected areas expansion.* In current biomass potential studies, usually nature conservation areas are excluded from biomass potentials, but besides little or no land is reserved for biodiversity conservation. The issue of which land can be used for biomass production without substantially decreasing biodiversity and nature conservation values and which land has to be excluded has not been resolved completely. The analysis indicates that excluding existing nature reserves – even though part of these could legally be used for biomass production – and future nature reserves does decrease estimated biomass potentials by about 25%.

The following issues are not covered within the quantitative analyses.

- *Food demands and human diets.* Assumptions on the future demand for food are crucial for estimating biomass potentials as in most studies it has been assumed that only land that is not needed for the production of food is available for biomass production [76]. Most estimates of biomass potentials that consider food demand and human diets are based on food demand projections of the FAO, representing a large range of possible future demands, depending on population developments and economic growth. Using these FAO projections estimate the difference between a scenario assuming low food demands and a scenario assuming high food demands to be about 130 EJ/year, while keeping other factors constant. Other studies [13] estimate this difference to be about 50 EJ/year.
- *Market mechanism food-feed-fuel.* If the use of biomass as fuel or as feedstock increases, prices of agricultural land and food will increase in the short term in addition to autonomous price increased due to population and income growth. This effect influences in turn supply costs of biomass and subsequently economic potentials, but also has impacts on food security issues that are

core of current biomass discussions. Some price effects have been calculated for first-generation biomass crops. For example in [99], world prices for first-generation biofuel crops increase between 6.5% for cereals and 10% for sugar under a mandatory blending according to the EU Biofuels Directive. However, the increase in biofuel use leads to a decline in crude oil prices by around 2%. Due to the fact that agricultural land is more or less a fixed factor, agriculture land prices react stronger on higher demand for biofuel crops as input for biofuel production. First results show that land prices in the EU increase strongly as a consequence of the biofuel directive. Land prices rise between 5% in the Netherlands and 15% in the UK. But further analysis needs to be done to achieve a more profound analysis of the key variables for the driving forces behind agro-production related to market developments such as price changes, technical progress, and policies.

- *Costs of biomass supply.* The costs of biomass supplies are important for the amount of biomass that can be used economically, that is, for the bioenergy demand. However, in energy demand models either static costs are used or cost-supply curves based on the availability of land after reserving land for other functions. In [4, 13] this was analyzed using the latter method, the amount of energy crops available at prices below 2 €/GJ which is about the price of coal. This amount is about 30–40% lower than the overall technical potentials. Given the nature of biomass supply curves used, no price effects of competition between resources (biomass for materials, food, agricultural land, water, nature conservation) are taken into account in the cost-supply curves that determine energy demands, even though they are relevant for modeling.
- *Use of by-products from agriculture and forestry.* By-products from food and wood production, for example, lignocellulosic residues, and from their processing, for example, rapeseed press cake, can be used for the production of bioenergy and for the production of animal feed. As second-generation conversion technologies are able to cope with lignocellulosic by-products from agriculture and forestry, a wider range of sources for bioenergy becomes available increasing biomass potentials

significantly. Additional to this potential of energy crops, thus, a considerable amount of about 76–96 EJ of residues from forestry, agriculture, and food and wood processing as well as secondary wastes are available at low costs [6]. Moreover, in the discussion of competition between food, feed, and fuel, the use of by-products as an animal feed has to be taken into account in order to assess the final effects on the feed market. This use of by-products potentially decreases the amount of biomass available.

- *Water use efficiency of crops.* The water use efficiency of crops depends on the type of crops as well as on agricultural management. For example, water use efficiencies in gram biomass per kilogram of water are about 1.7–2.2 for wheat, 2.5–3.8 for sugar beet, 4.0–6.4 for sugar cane, and 1–9.5 for lignocellulose crops [36]. Increasing water use efficiency of food crops as well as energy crops could reduce the competition for water resources between agricultural production and other uses, especially for irrigation-type systems. This increased water efficiency might in turn lead to higher biomass potential. To determine this effect, quantitative research on the amount of biomass available in rain-fed and irrigated agriculture depending on water availability and realized water on a regional and global level would be needed. However, only studies on a field level addressing these issues are so far available.
- *Climate change.* Climate change can influence the suitability of a certain area for biomass production as well as their “biodiversity value,” but limited research on the relationship between biodiversity, biomass production, and future climate change has been carried out. The GBO2 study shows a negative effect of climate change on biomass production and biodiversity [30]. These negative relations depend on the use of agricultural land that is not needed for food production and its restoration value as well as on the use of “more natural” areas. However, a decrease in the possibilities of annual crop production might lead to larger possibilities for perennial energy crops. Research into these complex correlations and feedback mechanisms has not been sufficient to quantify the impact of climate change on biodiversity and biomass potentials.
- *Alternative protein chains.* The production of proteins from animal farming uses large amounts of

land and other resources. Life-cycle assessment showed that a transition from animal to plant protein might result in a 3–4-fold lower requirement of agricultural land and about a 30–40-fold lower water use [41]. The land and water resources that could be made available by such a transition could then be (partly) used for biomass production and for relieving the pressure on biodiversity. The influence of changing protein sources for human consumption on biomass potentials could not be quantified within this study and has not been studied in the reviewed biomass potentials studies, but might be potentially large. An area of 25 Mha of soy would yield an amount of protein equivalent to livestock presently fed by 400 Mha of feed crops (300 Mha grains plus 100 Mha oilseeds), thus setting 375 Mha free [41]. (Even in this rough estimate, meat from grazing animals [beef, lamb, and goat] and from animals fed agricultural waste [pork] would still be available.) Changing protein sources requires technological change as well as a change of consumption patterns. Present trends, however, suggest meat demand to be increasing, rather than decreasing.

- *Demand for biomaterials.* Wood and fiber products (pulp, timber, boards, etc.) are the largest group of biomaterials currently produced. In studies considering all types of biomass resource, the demand for wood products is included, that is, the wood products demand is subtracted from the future biomass potentials. Smeets et al. [6] estimated the difference between high and low future demands for wood products in 2050 to be about 30 EJ/year. Chemicals and other biomaterials might become another important area for biomaterial use and are usually not included in biomass potentials estimates. However, demands for biomaterials are comparatively low (e.g., results from a scenario analysis on bio-based chemicals indicate that even in a scenario with high market potentials of bio-based chemicals not more than 10% of agricultural land in the EU-25 in 2050 will be used for bulk chemical production – assuming lignocellulosic feedstock [104]) and do not exclude the use of biomass for energy as cascading strategies, that is, first using biomass for food, feed, materials and then converting organic wastes to energy can be applied. In energy

demand models, the use of biomass as feedstock material is typically not included and the only global model that does take it into account predicts a limited, but not insignificant amount of biomass to be allocated to materials. As a consequence, coupling and integration of sector modeling (e.g., wood products, chemicals, forestry) to biomass potential estimates and is necessary.

- *GHG balances of biomass chains.* The biomass potential studies regarded do include biomass options regardless of their greenhouse gas balance. GHG emission reduction is an important driver of biomass use and might increase actual biomass demands, while on the other hand excluding biomass chains with low or negative reductions could lower biomass potentials. However, the possible influence of this latter aspect is small, as most potential studies are already based on lignocellulosic biomass and, thus, disregard unfavorable biomass chains such as first-generation fuels from annual crops and land-use changes from wetland and forests to energy crop production [101, 102].

In Table 3, the key uncertainties discussed are summarized and evaluated in view of their importance (column 2). Also the impact on biomass potentials as estimated in the literature reviewed is presented (column 3). For example, for the improvement of agricultural management it is indicated that biomass potentials increase or decrease compared to the estimates in recent studies. This means that the reviewed biomass potential studies used different values for agricultural efficiency that are within the ranges that were derived from our review. As a consequence, biomass potentials estimated in the recent studies could increase or decrease if other assumption on agricultural management improvements would be assumed. However, for protected areas it is indicated that biomass potentials decrease compared to the ranges estimated in recent studies, meaning that if the recent studies would have included protected areas, the estimated potentials would be lower.

In addition to these results of the inventory, the results of the integrating analysis are also presented (column 4) and percentages of supply refer to the DV-2 scenario in IMAGE that estimates biomass potentials of about 200 EJ/year. However, it should be

Biomass Resources, Worldwide. Table 3 Overview of uncertainties and their impact on biomass resource potentials [24]

Issue/effect	Importance	Impact on biomass potentials compared to	
Supply potential of biomass		Supply as estimated in recent studies	OECD-baseline scenario in IMAGE
Improvement agricultural management ^a	***	↑↓	↑ 40–65%
Choice of crops	***	↓	↓ 5–60%
Food demands and human diet	***	↑↓	n/a
Use of degraded land ^b	***	↑↓	↑ ca. 30–45%
Competition for water ^c	***	↓	↓ 15–25%
Use of agricultural/forestry by-products	**	↑↓	n/a
Protected area expansion ^d	**	↓	↓10–25%
Water use efficiency	**	↑	n/a
Climate change	**	↑↓	n/a
Alternative protein chains	**	↑	n/a
Demand for biomaterials	*	↑↓	n/a
GHG balances of biomass chains	*	↑↓	n/a
Demand potential of biomass		Demand as estimated in recent studies	Biomass supply as estimated in TIMER
Bioenergy demand versus supply ^e	**	↑↓	↓ 80–85%
Cost of biomass supply	**	↑↓	n/a
Learning in energy conversion	**	↑↓	n/a
Market mechanism food-feed-fuel	**	↑↓	n/a

Importance of the issues on the range of estimated biomass potentials: *** – large, ** – medium, * – small

Impact on biomass potentials: potentials as estimated in recent studies would: ↑ – increase, ↓ – decrease, ↑↓ increase or decrease – if this aspect would be taken into account

n/a: no quantitative analysis has been carried out in this study

^aIncreasing yield levels of food and energy crops by about 12.5% compared to the baseline (half the suggested improvement potential in the International Assessment of Agriculture Science and Technology Development) leads to an increase of about 40% of biomass potentials. Moreover, bringing 2050 technology levels in developing countries close to current Western European levels leads to an increase of up to 60% of potentials in 2050

^bThe potential of using severely degraded land (cat. 3 and cat. 4 of the GLASOD classification [103]) has been estimated to increase potentials by about 30% (cat. 3) and 45% (cat. 3 and 4)

^cOther main uses that compete with biomass production for water are agricultural, industrial, and domestic uses. Excluding areas with a water scarcity of >0.4 and of >0.2, respectively, leads to a decrease of estimated biomass potentials of about 15–25% in the analysis in [section "Integration of the Findings."](#) However, due to climate change, in future the number of regions with water scarcity will increase and competition for water will become more important

^dReserving nature reserves in areas designated to become nature reserves under the Sustainability First scenario of the Global Environmental Outlook of the UNEP leads to a reduction of up to 25% of biomass potentials

^eThe economic biomass potentials based on energy demand modeling is much smaller than the possible technical biomass supply. Starting from a biomass cost-supply curve with a maximum supply of 700 EJ/year in 2050, the energy demand at carbon taxes of 0–300 €/tC is only about 15–20% of the possible supply, that is, the economic potential is 80–85% lower than possible supply

noted that the results of the integration analysis provide an order of magnitude but are not based on an integrated modeling analysis.

In recent discussions about the large-scale development of biomass use for energy and materials, many issues around biomass potentials and linked areas such as water, biodiversity, food, energy demands, and economic developments play an important role. Below, a summary of knowledge and knowledge gaps concerning biomass potentials are given. Note that social impacts of biomass use and impacts on energy security – though of large political relevance – have not been an explicit part of this study. Also policies and their effects on biomass potentials have only been analyzed on a very limited level, that is, investigating the effects of carbon taxes on energy demand.

1. Are biomass potentials sufficient to supply a large part of future energy demands? (In the assessment of the German Advisory Council on Global Change that assumes a very limited availability of land due to nature protection and high food consumptions with at the same time very low crop yields, only about 70 EJ from residues and about 40 EJ from energy crops are estimated to be available [100].)

In principle, biomass potentials are likely to be sufficient to allow biomass to play a significant role in the global energy supply system. Under the assumption that food demands of future population are met, most recent studies estimate global biomass potentials of 300–800 EJ/year in 2050 for various scenario conditions. The analysis reported in this entry showed that under negative circumstances concerning land availability (i.e., excluding large areas for nature protection, mild to strong water-scarce areas, and mildly and severely degraded land from biomass production) only about 80 EJ/year from energy crops might be available, while an additional amount of about 80 EJ/year from residues and an additional amount about 60–100 EJ/year of surplus forest growth is likely to be available. At the same time, scenario analyses predict a global primary energy use of about 600–1,040 EJ/year [5].

Energy demand models that calculate the amount of biomass used if energy demands are supplied cost-efficiently at different carbon tax regimes estimate that in 2050 about 50–250 EJ/year of biomass are used, a range that is significantly lower than the estimated supply potential. For determining future economic potentials of bioenergy more exactly, however, an advanced integration of demand models with cost-supply curves of biomass and extended knowledge about technological learning in energy conversion technologies would be necessary.

2. What drives the economic competitive use of bioenergy and materials?

Most important in the economic part in the discussion around bioenergy is the fact that feedstock crops such as cereals, oilseeds, or sugar cane are in direct competition with food on the consumption side. For biomass such as willow or switchgrass, this competition is less stringent, but also in this case biomass production is in direct competition for scarce resources, especially land. Changes in relative prices between different crops and between different energy sources, that is, energy crop prices versus fossil energy prices, are the key drivers in future use of biomass. The economic analysis of biofuel use clearly shows that apart from direct policy measures, for example, mandatory blending commitments, this price ratio is the most significant driver in the use of biofuels. Any analysis of biofuel potentials which also takes economics into account must consider this key element. However, the dynamics are also important, because shifts in relative prices also trigger investments and technical progress in the biofuel sector which lowers in the long-term production costs and increases the long-term profitability of biofuel production.

3. What are the main sources of biomass?

Biomass for energy and material in 2050 is derived from three major sources: (1) residues and waste (about 5–20%), (2) surplus forest growth (about 5–15%), and (3) energy crops (about 60–80%). In the biomass potential studies, it is assumed that biomass is grown on surplus agricultural land that is not needed for food

production and partly on other types of land. This surplus land depends on the demands for food and material and the subsequent price effects.

4. What role might degraded lands play in biomass production?

Another question in determining future biomass potentials is whether degraded lands – of which productive capacity has declined temporarily or permanently – can be used for biomass production. At this moment the potential of the large area of degraded soils – classified as light and moderately degraded and covering about 10% of the total land area – to contribute to the production of biomass is not yet clearly assessed. This is because of the unknown impact of two possible drawbacks: firstly the large efforts and long time period required for the reclamation of degraded land and secondly the low productivity levels of these soils. In the integration analysis it has been shown that using severely degraded land would increase biomass potentials from energy crops by about 30–45%, assumed that in principle it would be possible. However, using severely degraded land for annual crop production might require large investments and many attempts for reclaiming degraded land for food production have failed. Other attempts with, for example, reforestation and agroforestry might be more promising for biomass production and some projects in the past on, for example, saline soils have been successful. Further research on the potential of degraded soils for biomass production is needed. Preferably, other mitigation options (carbon storage in soils and vegetation) and adaptation options should be integrated in the research on the potential of degraded soils for biomass production.

5. What determines biomass yields?

It should be noted that the conclusion that future biomass potentials are large enough to play a relevant role in supplying a significant part of future energy demands depends on land availability (see above) and on biomass yields. Ranges of assumptions on land availability in the reviewed literature influence total technical biomass potentials more strongly than the estimated ranges of

biomass yields. Biomass yields depend mainly on the development of agricultural management and the choice of crops. First, most recent biomass potentials studies assume that the efficiency of agricultural production improves in the coming decades assuming low to high technology development rates. (For illustration, extreme scenarios that assumed extensive agriculture or high advanced technologies with landless animal production resulted in estimated future global biomass potentials of about 0 EJ/year and 1,500 EJ/year, respectively.) Practice, however, shows that deployment of agricultural technologies in developing countries can be a difficult task and implementation strategies need to be studied very well. Second, all estimates of future biomass potentials discussed are based on the use of perennial lignocellulosic biomass in 2050. This necessitates the availability of second-generation conversion technologies for the production of biofuels and most chemicals. Perennial lignocellulosic crops have in general higher yields than annual sugar, starch, and oilseed crops, while perennial sugar and oil crops (e.g., sugar cane, palm oil) have high yields too. Calculations in the integration part of this study indicate that potentials for annual biomass crops, that is, maize, might be very low and not sufficient to provide a large part of energy demands.

6. Is water a limiting factor for biomass potentials?

In general, water availability can be a limiting factor for the production of biomass and food. A simple and rough analysis in this study has shown that excluding water-scarce areas decreases the biomass potentials by about 15–25% for woody bioenergy crops in 2050, in a scenario with biomass potentials about 200 EJ/year (and thus excluding residues and learning in agricultural management). Water availability, however, has not been analyzed on a sufficiently detailed spatial level to estimate regional biomass potentials in water-scarce areas. Another remaining point of uncertainty is the possibility to increase water use efficiency in agriculture and as such increasing biomass potentials. A regional to local analysis is necessary to further evaluate this

possibility. Finally, climate change will increase variability of rainfall patterns. It is expected that in the subtropics and some already water-scarce areas rainfall will decrease, while at high latitudes it will increase. For the tropics, estimates of future rainfall vary.

7. What is the relation between biodiversity conservation and using bioenergy?

Studies that estimate biomass potentials assume that nature conservation areas are excluded from biomass production, as such estimated biomass potentials consider biodiversity conservation on a base level. Assuming that larger parts of land should not be used for biomass production for reasons of biodiversity conservation, potentials would decrease accordingly.

In most cases perennial lignocellulosic crops have lower impacts on biodiversity than annual sugar, starch, and oilseed crops and are, thus, better suited for combining biodiversity and biomass production. Important open questions in this area are:

- To what degree is the potential energy production on a certain piece of land related to the (potential) biodiversity value of the same piece of land if reserved for nature?
- How to measure biodiversity, realizing that different available indicators tell different stories?
- What are the effects of future climate changes on biodiversity (very uncertain) and areas for biomass production (more certain)?

8. What is the effect of biomass use on food prices?

Economic analyses indicate clearly that food prices increase with an increased demand for biomass, but the magnitude of this increase is uncertain. In the long term, price increases might accelerate agricultural efficiency leading to larger potentials of food and biomass production and mitigating price increases. For example, OECD and FAO project a price increase of coarse grains prices of about 30% in the short term and about 10–20% in the medium term (2010–2016) compared to the 1996 level. At the same time, prices of sugar are projected to increase by about 30–40% and then even to decrease compared to the 1996 level [56]. Only part of these projected price

developments is due to the increase of biofuel production, while other parts are due to low recent harvests and increasing other demands. This analysis indicates clearly that land, food, and energy demand are linked via prices. Thus, a priori not a certain area will be reserved for food production, but economic mechanisms determine the distribution of land uses. For annual crops that are used for the production of first-generation biofuels, the linkage between food prices and biofuel demands is probably larger than perennial lignocellulosic crops used for second-generation biofuel production. This is due to direct competition. However, currently agricultural models do not include and analyze second-generation biofuels and knowledge on the impacts of second-generation biofuels on food prices is lacking. Finally, while large amounts of biomass can be used without jeopardizing future global food demands, it should be noted that food availability and affordability are very regional and that these future regional distributions of food and energy supplies are not sufficiently known yet. Here, further knowledge including the influence of policies and subsidies on food security especially in developing countries is needed.

9. How should the available biomass be used?

Energy demand models show that the optimal use in terms of cost-efficient energy supply depends on future technological development of bioenergy technologies as well as alternative technologies. Other major drivers found for directing biomass use are greenhouse gas emission reductions, carbon taxes, and oil prices. Thus, cost-efficient optimal biomass use strongly depends on future developments. From a greenhouse gas perspective, second-generation biofuels are in most cases more efficient than first-generation biofuels, while the comparison between second-generation biofuels and electricity depends on energy conversion technologies as well as fossil references for electricity production. Using biomass for materials, for example, for construction and chemicals, and the cascading of these materials can be attractive from a greenhouse gas reduction perspective. Compared to energy, however, markets for biomaterials are rather small.

10. What types of analyses are still needed?

This review gives an overview of the most important linkages between the areas of water, food, biodiversity, economic effects, energy demands, and biomass potentials. While knowledge and knowledge gaps in these areas have been discussed above an integrated analysis of these areas is still missing. Important issues in such an integrated analysis are as follows:

- Drivers and barriers in the food-feed-fuel nexus that could be used to refine modeling and scenario analysis of geographical and economic biomass potentials
- Linkages between the availability and prices of water, the availability and prices of land, the demand for food and feedstock, the demand for energy, and between the cost-supply curves of biomass
- Regional analysis that analyzes the relation between food security, biomass potentials, water availability, and land-use changes on a spatially explicit level
- Mechanisms of changes and the implications of policy instruments in different parts of the world

Conclusions and Future Directions

Current understanding of the potential contribution of biomass to the future world's energy supply indicates that the total supplies could amount from a minimal 100 up to 1,500 EJ theoretical potential (compared to some 450 EJ current global primary energy demand). This assessment gave a much more sophisticated view on the factors and biomass resource categories that explain the ranges, which are particularly caused by the way food demand and agricultural management develops and by uncertainties to what extent more marginal and degraded lands may be deployed for biomass production. The potential consists of three main categories of biomass:

1. Residues from forestry and agriculture and organic waste, which in total represent between 40 and 170 EJ, with a mean estimate of around 100 EJ. This part of the potential biomass supplies is relatively certain, although competing applications may push the net availability for energy

applications to the lower end of the range. The latter needs to be better understood, for example, by means of improved models including economics of such applications.

2. Biomass produced via cropping systems on possible surplus good quality agricultural and pasture lands. This part of the potential biomass supplies is the most significant and can amount up to over 300 EJ for the high-level improvement for agricultural efficiency included in the SRES scenario range. It is also a more uncertain category. The key factor determining net availability of land is improvement in efficiency in agriculture and livestock production systems. From a technical perspective, potential efficiency increases are very large seen on a global basis, especially in developing countries as is highlighted in [6]. However, the speed at which such improvements may be realized is uncertain and depends on a wide variety of factors which are partly poorly understood and manageable. In particular the economic drivers for such developments require further attention. The lower estimate given in this study based on the OECD scenario results in biomass supplies from energy crops up to 120 EJ (which includes corrections for water scarcity, land degradation, and new land claims for nature reserves; see also the third category below). A "compact agriculture scenario" (roughly similar to the A1 and B1 SRES scenarios) would add some 140 EJ to that estimated 120 EJ, resulting in a range of 120–260 EJ.
3. The use of marginal and degraded lands that are not used for food production. This aspect is addressed in some more detail in this assessment. Although it should be recognized that data quality on such soils is fairly weak, that land-use scenarios in this respect are crude, and that knowledge to what extent different types of vegetation can be established has seen limited study, some global estimates have been compiled. The potential contribution could add about 70 EJ to the production of energy crops EJ, but this would include a large area where water scarcity provides limitations and soil degradation is more severe. The lower estimate, covering more limited degradation and water scarcity, represents the 120 EJ discussed above. This lower estimate also incorporates estimated additional demand for new nature reserves.

The key uncertainties for this category are the extent to which such lands can really be utilized for biomass production from a technical and economic perspective and to what extent nature and biodiversity conservation may conflict with the partial use for biomass harvesting, since marginal and abandoned lands do represent varying levels of biodiversity. Management, harvest, and trade-offs with biodiversity need to be assessed on a regional scale. Another important element is to what extent increased food demand may make it more attractive to use marginal lands for food production in the future and thus compete with bioenergy. Such dynamics can still not be investigated by current modeling tools.

The level of knowledge on this category is relatively poor and the lands in question in fact cover a wide variety of different settings, from semiarid lands to degraded lands in various degrees to soils affected by salinity, etc. On the one hand, use of such lands for biomass may be very attractive because conflicts with food production are far less up to absent compared to arable lands. Furthermore, important co-benefits may be achieved such as regeneration of soils, improved water retention, and (some) regained economic activity, which may prove even more important drivers than biomass production for energy alone. On the other hand, obtaining sustained biomass production, be it with low productivity, may bring higher costs.

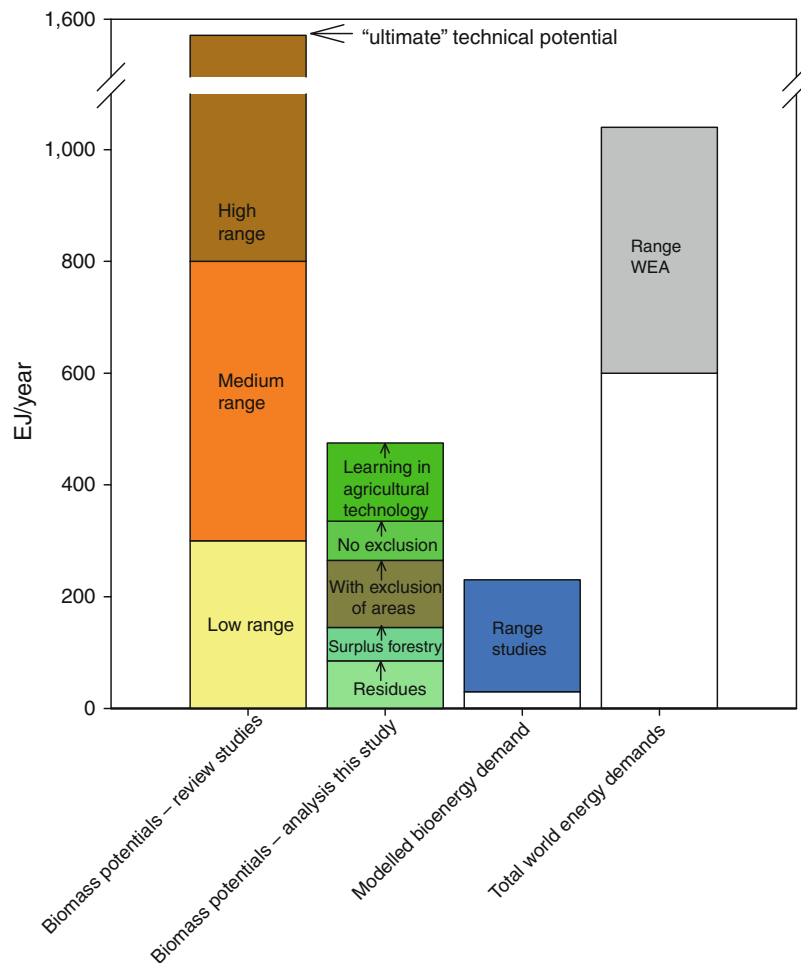
Overall (Fig. 15), this assessment tuned the broad range of estimates of global biomass resource potentials down to a range of minimally 200 EJ up to more than 500 EJ.

Another result of this assessment (but also confirmed by the IPCC fourth assessment report and the new IPCC report on Renewable Energy Sources [2, 53]) is that current energy scenarios which include GHG mitigation strategies following IPCC guidelines indicate that the demand for bioenergy until 2050 could in fact be limited compared to the potential biomass supplies, because various other options are more competitive in terms of specific mitigation costs. This may in particular be true for the use of biomass for power generation because other alternatives (such as wind energy, fossils with CCS, and nuclear energy) are more attractive at marginal biomass costs above ca 3 US\$/GJ. The estimated demand for primary biomass

reported in this assessment (based on MARKAL and TIMER model results) amounts maximally ca. 150 EJ, with ranges in other models of about 50–250 EJ. This is basically within the range of the indicated biomass resource potentials. In particular, the residues and wastes can cover a very significant part of the demand to start with. Specifically, production of transport fuels (based on lignocellulosic biomass via second-generation technologies) is expected to play a dominating role on medium term. Biomass use for materials and feedstock adds to the demand, but is a minor factor in total demand based on most current model results, although this area has still received limited attention. It should be noted though that the indications given by the IPCC, MARKAL, and TIMER are based on relative cost-effectiveness (e.g., costs per ton of CO₂ emission avoided). Other drivers, such as energy security and rural development could result in sustained policy support in particular for biofuels. This may increase demand for biomass considerably. In addition, the total energy demand is uncertain and in the higher projections, biomass demand may rise well over the indicated 150 EJ.

It should be noted that the energy model results are in particular sensitive to assumptions on the expected performance of advanced conversion technologies (such as second-generation biofuel production processes). It should also be noted that there is a wide range of energy models available which may yield different results than listed here. The main drivers for biomass demand though will not be different using other models.

The key studies that provided an important basis for the potential estimates mentioned are [4, 6, 13]. Given that those are among the most recent studies available and that in particular the Hoogwijk study already incorporated various limitations with respect to nature areas, low-productive areas, etc., these played an important role. The IPCC SRES scenarios used in the Hoogwijk analyses were used as a basis for this assessment as well, varying agricultural efficiency and using the base land-cover simulations of the IMAGE model. This assessment has provided several corrections of the available results to date, especially with respect to water availability, soil quality, and protected areas (which were excluded from the potentials for biomass production). These are significant and led to



Biomass Resources, Worldwide. Figure 15

Comparison of technical biomass potentials with bioenergy demands in 2050. Biomass potentials as analyzed in this study refer to the OECD-baseline scenario of IMAGE. (Exclusion of areas is the exclusion of mildly and severely degraded and water-stressed areas as well as the exclusion of areas designated as current and future nature reserves, while learning in agricultural technology reaches levels as assumed in the SRES A1 scenario.) [25]

corrections to earlier estimates of the resource potentials as argued above. Table 4 lists the key factors that influence that size of the potential.

This assessment also showed different trade-offs from biomass/bioenergy production on biodiversity. From a perspective of global biodiversity targets, different spatial scales and both short- and long-term effects must be taken into account. On a local scale, biodiversity may benefit from growing biomass, when intensive agricultural practices are replaced by low-intensity biomass production systems (such as short-rotation forestry, mixed land-use systems). The large

variation recorded in local effects deserves further attention for defining favored management practices. On a global scale, however, agricultural lands may only become available when food production regions will shift, for instance through trade liberalization. Thus, the short-term global biodiversity effects are intimately related to global land-use dynamics and especially the different causes of land abandonment. On the long term, biomass production is expected to contribute to reduced greenhouse gas emissions and, therefore, reduced climate change effects on biodiversity. A first-order estimate indicates that the balance between

Biomass Resources, Worldwide. Table 4 Overview of uncertainties and their impact on biomass resource potentials and recommended activities to reduce uncertainties

Issue/effect	Importance	Recommended activities to reduce uncertainties
<i>Supply potential of biomass</i>		
Improvement agricultural management	***	Research to better understand how efficiency and livestock can be increased in a sustainable manner and for different settings. Insight in development pathways and feasible rates of improvement need to be integrated in modeling frameworks. Improved insights in preconditions for improvements can provide a basis for targeted policies
Choice of crops	***	There are clear recommendations on the importance of lignocellulosic biomass production systems for different settings. Under certain conditions, sugar cane and palm oil could still be feasible options on longer term as well. Much more market experience with such production systems needed in different settings, including degraded and marginal lands, intercropping schemes (e.g., agroforestry), and management of grasslands. The latter is an important land-use category on which current understanding and data needs improvement
Food demand	***	Increases in food demand beyond the base scenarios (e.g., up to nine billion people in 2050) that were the focus in this study will strongly affect possibilities for bioenergy. Vice versa, limited population growth will mean the opposite
Use of degraded land	***	Represents a significant share of possible biomass resource supplies. Experiences with recultivation and knowledge on these lands (that represent a wide diversity of settings) are limited so far. More research is required to assess the cause of marginality and degradation and the perspectives for taking the land into cultivation. Research and demonstration activities required to understand the economic and practical feasibility of using degraded/marginal land is needed. This land-use category also requires attention (e.g., via better databases) in modeling efforts
Competition for water	***	Increased water demand for conventional agriculture, domestic, and industrial use is a concern in various world regions, with agriculture being by far the most important sector in this respect. This assessment provided a first-order insight in how (energy) crop production potentials may be constrained by water availability, which is significant already in some regions and will increase in the future. Constraints in water supplies and sustainable management need ultimately to be studied at water basins scale, in interaction with local scales
Use of agricultural/ forestry by-products	**	Residues are an important resource category. The net availability for energy purposes can in the future in particular be affected negatively by competing applications (e.g., biomaterials and traditional biomass use). Their net availability can be improved by better infrastructure and logistics. Key areas for research and sustainable management are maintaining sound organic matter levels in soils and nutrient balances. To some extent (especially for residues in tropical regions) more research and field experience to determine such levels is desired
Protected area expansion	**	Increased ambition levels for nature reserves on a global scale can have a significant impact on net land availability for biomass production. Land exclusion assumptions in the available studies, however, seem to overlap with the potential future land claims for nature and further modeling work and improved databases are desired. Furthermore, more insights are desired in how land-use planning including new bioenergy crops can maximize biodiversity benefits. Evaluating biodiversity impacts on regional level is still a field under scientific development and more fundamental work is needed in this arena

Biomass Resources, Worldwide. Table 4 (Continued)

Issue/effect	Importance	Recommended activities to reduce uncertainties
Water use efficiency	**	See above under competition for water. An important factor in the equation is improvement of water use efficiency in both current agriculture (that could be achieved through efficient management adapted to the local production situation, increasing resource use efficiency) and in biomass production itself. Technical improvement potentials are considerable compared to current average practice. This suggests that for various areas water management is a prime design parameter for sustainable biomass production and land-use management. This area deserves considerable further research efforts, preferably linked to field experience and the socioeconomic environment
Climate change	**	The impact of climate change on agricultural production and productivity of lands could be significant, but exact effects are also uncertain. Effective mitigation strategies, of which large-scale bioenergy deployment could be a significant element, will limit the influence of this factor. At this stage, this is still the objective of the governments that have signed the Kyoto Protocol Varying reported effects of climate change on natural systems and their biodiversity deserve further attention. Especially, variation due to using different indicators and modeling concepts should be better explained. This will influence the balance between land-use dynamics and avoided climate change effects Furthermore, although agriculture may face serious barriers due to climate change, this may also enhance the need for alternative adaptation measures to avoid soil losses and maintain vegetation covers. Biomass production (again especially via perennial systems) may then play a role as adaptation measure. Such strategies (under different climate change scenarios) are so far hardly studied and deserve further attention in future research efforts and scenario analyses
Alternative protein chains	**	See above under food demand. Possible but very uncertain reversal of current diet trends, i.e., introduction of more novel plant protein products (as alternative for meat) could on the longer term strongly reduce land and water demand for food. Such options and the feasibility in terms of implementation are, however, insufficiently studied. Further work in this area is recommended
Demand for biomaterials	*	Demand for biomass to produce biomaterials (both conventional as building material as new ones as bulk bio-based chemicals and plastics) can be a significant factor, but is limited due to market size (compared to demand for energy carriers). Furthermore, biomaterials will also end up as (organic) waste material later in their lifecycle, indirectly adding to increased availability of organic wastes. In many cases this "cascaded use" of biomass increases the net mitigation effect of biomass use. For some biomaterial markets specific cropping and plantation systems may be required due to demands of the biomass composition. Biomaterials are so far poorly integrated as a factor in energy models and as mitigation option. This can be improved in further work to understand the interactions between different flows and markets better (also in macroeconomic terms)
GHG balances of biomass chains	*	The net GHG performance of biomass production systems is not identified as a limiting factor for the potential, provided perennial cropping systems are considered. Also, striving for biomass production that is similar or better than previous land use (e.g., grasslands that remain grasslands or trees that replace annual crops) generally improves the overall carbon balance. This can also be true for replanting of degraded lands. The key factor in the net carbon balance is leakage. Avoiding leakage is directly related to increased efficiency in agriculture and livestock and net carbon impacts of biomass production should include this dimension. Such dynamics should ideally also be incorporated in future modeling exercises

Biomass Resources, Worldwide. Table 4 (Continued)

Issue/effect	Importance	Recommended activities to reduce uncertainties
<i>Demand potential of biomass</i>		
Bioenergy demand versus supply	**	The data on potential biomass demand in future energy scenarios reported in this study hint that biomass demand may in fact be lower than the biomass supplies that could be generated in baseline scenarios used (as "OECD Baseline"). At ambitious levels of climate change abatement, the key demand factor is likely to be the use of biomass for transport fuels due to the very few alternatives available for oil and reducing CO ₂ emissions in the transport sector. Nevertheless, long-term energy demand projections are also characterized by considerable variability (especially caused by GDP and population growth and the rate of deployment of energy efficiency measures at large). Demand for transport fuels, e.g., could therefore also be significantly higher than projected in this report and this could be further enhanced when policies target increased energy security and rural development as other priorities that are likely to favor biomass and biofuels. It is recommended to incorporate (dynamic) biomass supply projections and a more diverse portfolio of conversion options (e.g., including hydrogen production from biomass and combined with CCS) in current models to obtain more coherent analyses and scenarios.
Cost of biomass supply	**	The costs of biomass supplies are influenced by the degree of land-use competition, availability of (different) land (classes), and optimization (learning) in cropping and supply systems. The latter is still relatively poorly studied and incorporated in scenarios and (energy and economic) models, which can be improved. Nevertheless, the variability of biomass production costs seems far less than that of oil or natural gas, so uncertainties in this respect are relatively limited.
Learning in energy conversion	**	See remarks on energy models and costs of biomass supply; better insights in development potentials of key technologies (second-generation systems) and biomass supplies will improve the quality of scenario results with respect to the relative role of biomass for energy (and materials).
Market mechanism food-feed-fuel	**	To date, limited modeling efforts are available to fully interlink macroeconomic/market models with biomass potential studies, especially when lignocellulosic biomass is concerned. To date, price dynamics and, longer-term, responses of agriculture (in terms of increased land use and/or increased efficiency) are also addressed to a limited extent. Although the long-term impacts on actual physical biomass resource potentials may be limited, understanding the economic responses to increased demand for food and bioenergy and how these affect the relative competitiveness of bioenergy compared to other energy supply options is extremely important for defining balanced policy strategies. Linked to this, socioeconomic implications (such as impacts on rural income, rural employment) should be further understood.

Importance of the issues on the range of estimated biomass potentials: *** – large, ** – medium, * – small

global biodiversity losses from increased land use and reduced climate change effects from biomass production alone is not beneficial for biodiversity within 50 years. However, this conclusion is surrounded by considerable uncertainty, especially on climate change effects and also with respect to net biodiversity values of vegetation patterns and cropping systems. The latter

may be strongly influenced by good practices and governance of land use. This element deserves further research.

As summarized, the size of the biomass resource potentials and subsequent degree of utilization depend on numerous factors. Part of those factors are (largely) beyond policy control. Examples are population growth

and food demand. Factors that can be more strongly influenced by policy are development and commercialization of key technologies (such as conversion technology for producing fuels from lignocellulosic biomass and perennial cropping systems), for example, by means of targeted RD&D strategies. Other areas are:

- Sustainability criteria, as currently defined by various governments and market parties.
- Regimes for trade of biomass and biofuels and adoption of sustainability criteria (typically to be addressed in the international arena, e.g., via the WTO).
- Infrastructure; investments in infrastructure (agriculture, transport, and conversion) is still an important factor in further deployment of bioenergy.
- Modernization of agriculture; in particular in Europe, the Common Agricultural Policy and related subsidy instruments allow for targeted developments of both conventional agriculture and second-generation bioenergy production. Such sustainable developments are, however, crucial for many developing countries and are a matter for national governments, international collaboration, and various UN bodies (such as FAO).
- Nature conservation; policies and targets for biodiversity protection determine to what extent nature reserves are protected and expanded and set standards for management of other lands.
- Regeneration of degraded lands (and required preconditions) is generally not attractive for market parties and requires government policies to be realized.

Although this assessment was not specifically targeting formulation or further design of sustainability criteria for biomass production, the results provide leads for further steps for doing so. For criteria framework as developed in many places, it is evident that a number of important criteria require further research and design of indicators and verification procedures. This is in particular the case for the so-called macro-themes (land-use change, biodiversity, macroeconomic impacts) and some of the more complex environmental issues (such as water use and soil quality) [105].

This study has confirmed that in principle technical and economic biomass resource potentials could be very large on a global scale (up to one third of global

energy demand following more average projections for energy demand as well as biomass resource potentials). However, only a smaller part of the larger potential estimates will be almost certainly available (namely, the biomass residues and organic wastes). The larger part of the potential has to be developed via cultivation and has to meet a wide variety of sustainability criteria to avoid conflicts with respect to water use, land-use competition, protected areas, biodiversity, soil quality, and socioeconomic issues. Based on the findings in this assessment, for large parts of the resource potentials the indications are that such conflicts can indeed be avoided or may in parts even result in co-benefits. The latter could be true for using some categories of degraded lands (impacts on soils, water use, and biodiversity), combined strategies for modernization of agriculture, and diversification of cropping patterns (e.g., intercropping, agro forestry systems).

Both in size and in terms of meeting this wide array of criteria, annual food crops may not be suited as a prime feedstock for bioenergy. Perennial cropping systems, however, offer very different perspectives. These cannot only be grown on (surplus) agricultural and pasture lands, but also on more marginal and degraded lands, be it with lower productivity. Such cropping system represent a very diverse set of possible production systems, from low-intensity forestry and managing existing grasslands to highly productive plantations with short-rotation coppice systems or energy grasses like *Miscanthus*. At this stage, there is still limited (commercial) experience with such systems for energy production, especially considering the more marginal and degraded lands and much more research and demonstration work is needed to develop feasible and sustainable systems suited for very different settings around the globe. This is a prime priority for agricultural policy.

Most challenging in harnessing biomass production potentials in a sustainable way is probably the design of governance and implementation strategies. Such strategies should allow for gradual introduction of biomass cropping systems into rural regions and simultaneously increasing agricultural and livestock productivity. As confirmed by this study, those productivity increases are an essential component to avoid conflicting claims on land and to strong competition (e.g., via increased prices for food). This assessment as

a whole points out that policies targeting development of bioenergy use and biomass production should incorporate a variety of targets and boundaries. Fulfilling a strict GHG criterion (e.g., 90% compared to reference fossil energy use) will lead to different choices for crops and land management compared to a situation where no criterion is formulated. This is also true for sustainable management of water resources, biodiversity, as well as rural development. Clearly, the balance of objectives will be different from setting to setting (e.g., compare rural Africa with the EU) and trade-offs have to be made. It is argued here that such trade-offs should be explicit, balanced, and should incorporate clear boundaries that should be respected and used as a starting point for developing biomass production in a given region. Governance and deployment of incentives (such as subsidies or obligations) could then also be designed to achieve just that. This is a fairly sharp contrast to some of the current biofuel policies implemented in the EU and the USA.

Note

This entry is to a considerable extent based on a reworked version of the following publication: Veronika Dornburg, André Faaij, et al. *Biomass Assessment: Assessment of global biomass potentials and their links to food, water, biodiversity, energy demand and economy – Main Report*, Netherlands Research Programme on Scientific Assessment and Policy Analysis for Climate Change. Report no: WAB 500102012, January 2008, p 85 + Appendices.

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Biomass to Liquid (BtL), Concepts and Their Assessment

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Article Outline

Glossary
 Definition of the Subject
 Introduction
 Production Pathways on Synthetic Fuels
 Technical Assessment
 Economic Assessment
 Environmental Assessment
 Conclusions
 Future Directions
 Bibliography

Glossary

ADP Abiotic depletion potential
 AP Acidification potential
 bf Biomass feedstock

BtL	Biomass to liquid
CAPEX	Capital expenditures
CED	Cumulative energy demand
CH₄	Methane
CHP-F	Combined heat, power, and fuel generation
CML	Centrum voor Milieukunde Leiden
CO	Carbon (mono-)oxide
CO₂	Carbon dioxide
CtL	Coal to liquid
DE	Diesel equivalent
DME	Dimethylether
EP	Eutrophication potential
eq	Equivalent
EU	European Union
€	Euro
FOW	Forest wood
FT	Fischer–Tropsch
GtL	Gas to liquid
GWP	Global warming potential
H₂	Hydrogen
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
MeOH	Methanol
MF	Maximum fuel
MISC	Miscanthus
MJ	MEGA Joule
NMVOC	Non-methane volatile organic compounds
OPEX	Operational expenditure
P	Power
pkm	Passenger kilometer
POCP	Photochemical oxidation
R&D&D	Research and development and demonstration
SNG	Synthetic natural gas
SP	Starting point
SRC	Short-rotation coppice
SS	Self-sufficient
STR	Straw
TCI	Total capital investment
ZnO	Zinc oxide
η	Efficiency

Definition of the Subject

To meet future policy and technical targets, biofuels of the next generation need to be developed in parallel to

the existing biofuel generation. However, there is no silver bullet yet that of the various discussed options for next generation biofuels (e.g., bioethanol, synthetic biofuels, biohydrogen based on lignocelluloses, biomethane) will become widely accepted within the future transportation sector. BtL fuels (biomass to liquid) are one option of future biofuels that has center stage of discussion due to favorable fuel properties. Therefore different concepts for BtL provision have been analyzed and compared by technical, economic, and environmental criteria. This is done to perform a consistent comparison of BtL concepts being currently under development (e.g., [1, 2]).

Introduction

Despite national trends due to a strong increase of mobility of goods and persons, the energy demand for transportation purpose will increase significantly in Europe, America, and Asia (globally about 26% until 2020 compared to 2005) [3]. Although this sector will continue to primarily ask for crude oil products, hope is given for increased energy efficiency and maybe electro mobility in the years to come. Biomass is of particular interest within the ongoing discussion on sustainable mobility due to its advantages concerning, e.g., climate relevance and security of supply. In developed and developing countries, fossil fuel price fluctuations, climate change issues, as well as supply security aspects have resulted in significant growth in the interest on biofuels. This development will probably increase independently from the also ongoing debate on food security and sustainability issues.

To meet future targets, besides other promising biofuel options, BtL (i.e., biomass to liquid, especially Fischer–Tropsch fuels) have taken a center stage in the ongoing discussion due to its favorable fuel properties as synthetic designer fuel (e.g., regarding heating value, high cetane number, promising cloud point, low aromatic and polyaromatic content) and thus the opportunity to implement BtL fuels without any adaptation into the existing infrastructure of fuel distribution and use.

Within this paper selected BtL options are analyzed and assessed under European frame conditions. Different concepts for BtL provision are compared by technical, economic, and environmental criteria. This is done to perform a consistent comparison of BtL

concepts currently under development and to show both pros/cons as well as prospects/risks of the BtL systems from different viewpoints.

Production Pathways on Synthetic Fuels

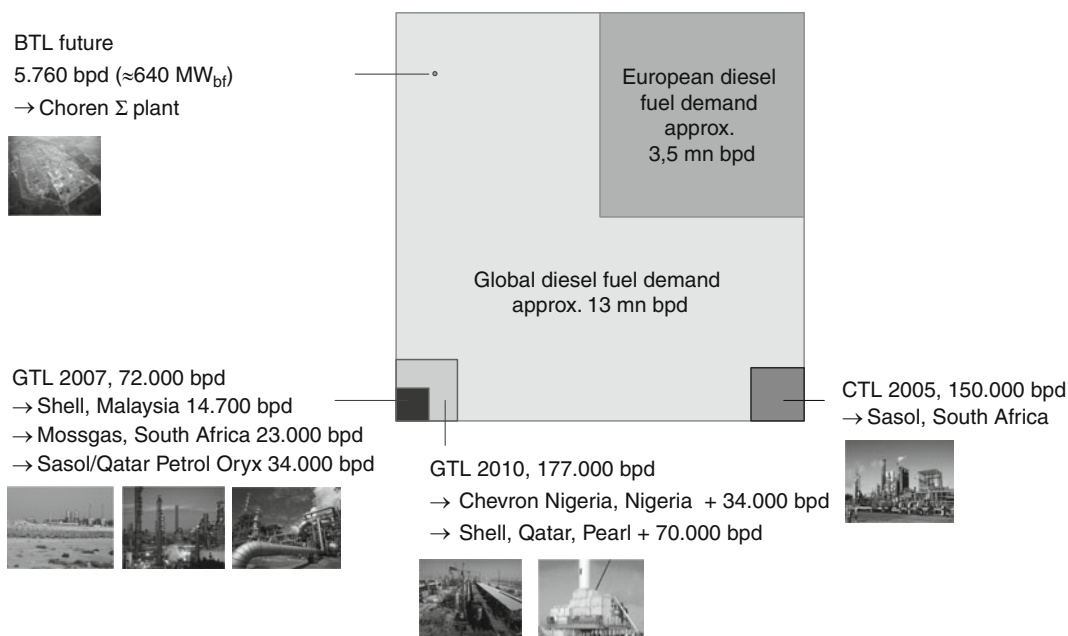
XtL is a synonym for the production of synthetic liquid fuels from different raw materials. Gas to liquids (GtL) or coal to liquids (CtL) are currently the most important industrial processes for synthetic (liquid) fuel production. Concerning the fuel synthesis part, XtL use similar technologies (basically Fischer–Tropsch (FT) synthesis) but the raw materials and synthesis gas production – and therewith also technical aspects – are different. Due to historic and economic reasons, commercial XtL plants show different sizes and plant capacities. So far, primarily Fischer–Tropsch technologies have been implemented at industrial scale and are being further developed in new industrial GtL projects mostly in Qatar. The differences in the plant sizes between BtL and GtL/CtL do not obligatorily lead to completely new process designs along the BtL provision chain. There are many similarities of the production routes of current commercial XtL and future BtL plants. The relation of typical capacities of XtL plants

being installed or planned as well as the diesel fuel demand in Europe is shown in Fig. 1 [4].

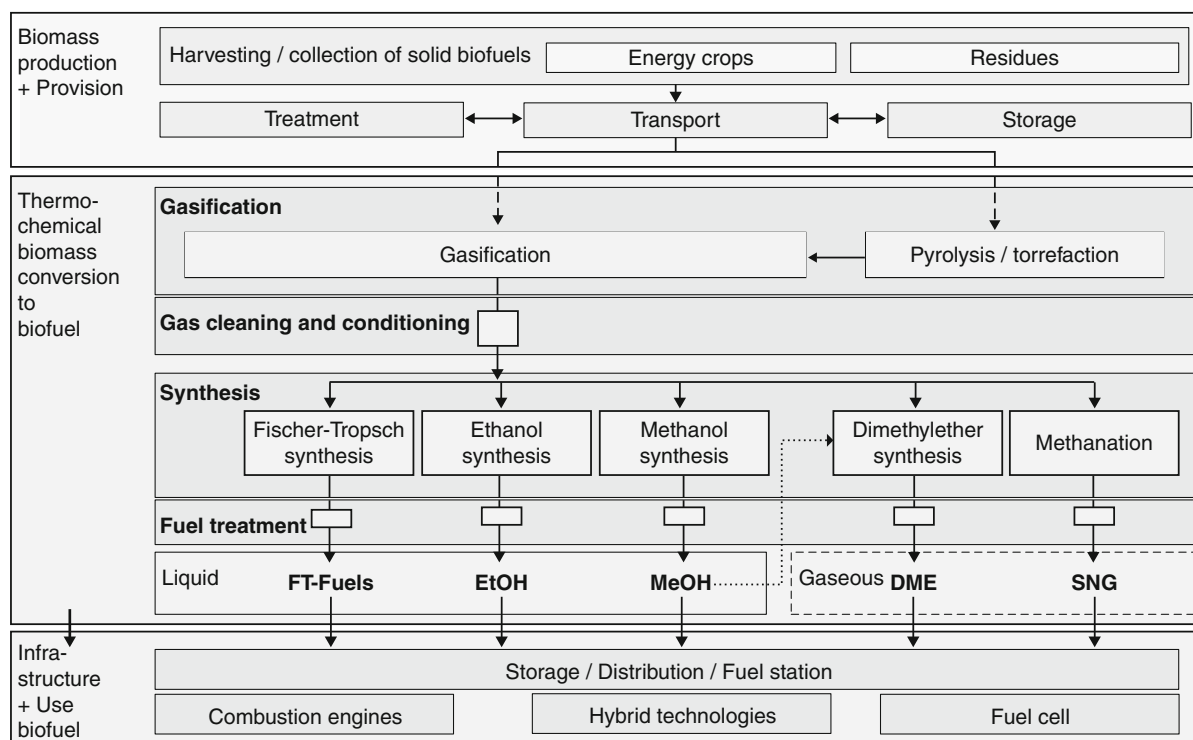
BtL Production Pathways

The production of synthetic fuels and intermediate products (i.e., “designer fuels” with clearly defined properties) is characterized by three main steps after appropriate biomass pretreatment: (1) gasification of lignocellulosic biomass to a raw gas, (2) cleaning and conditioning of raw gas to synthesis gas, (3) catalytic synthesis of this gas to synthetic biofuels (e.g., FT, MeOH, DME, and SNG), and (4) final product treatment. The principle is shown in Fig. 2.

Regarding biomass pretreatment for gasification, the mechanical-thermal biomass treatment (e.g., chipping and drying of solid biofuels) is technically mature. But processes to produce intermediate products that can be easier transported and handled for gasification (i.e., pyrolysis and torrefaction) are in the pilot/demonstration stage. Despite the scale of a gasifier, no gasification system is a priori appropriate for biomass. Among other criteria, chemical characteristics, physical and mechanical properties of the utilized biomass are important. However, basically all



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 1
XtL capacities (>1,000 bpd) worldwide



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 2

General overview of synthetic biofuel routes

types of gasification reactors for biomass (e.g., fluidized bed and entrained flow reactor) are still under development up to now. Furthermore, previous developments on gasification were mostly not focused on synthesis gas production but rather on the use of product gas for CHP generation [5–10].

Primarily with regard to the gas purity and the H_2/CO ratio, specific qualities of synthesis gas at constant compositions and large amounts have to be achieved depending on fuel synthesis (e.g., for the production of 100–1,000 m^3_{STP}/h of FT). Because no gasifier system meets these requirements so far, appropriate gas cleaning and conditioning systems have to be applied. During gasification, in addition to the main components (CH_4 , H_2 , CO , CO_2), impurities also are generated such as tars, coarse and fine particles, sulfur compounds, alkalis, halogen and nitrogen compounds, as well as heavy metals. Their quantities vary depending on the gasification process. For raw gas cleaning alternatively low temperature wet gas cleaning or hot gas cleaning can be used. The effectiveness of wet gas

cleaning (e.g., cyclone and filter, scrubbing based on chemical or physical absorption) has been well proven for large-scale coal gasification systems. Different to that, not all elements of hot gas cleaning (e.g., tar cracking, granular beds and filters, physical adsorption or chemical absorption, ZnO -bed, physical absorption) are technically mature yet. Nevertheless, hot gas cleaning offers benefits for the overall energy balance with regard to the avoidance of contaminated sewage. Available system components can be applied for gas conditioning: Hydrocarbons in the product gas can be converted by means of a steam or autothermal reforming step resulting in a higher H_2/CO ratio. To achieve the required quality for fuel synthesis the water gas CO shift conversion is conducted as final step of synthesis gas production [8, 11–18].

Promising BtL Concepts

At present the provision of synthetic biofuels is under discussion for various processes and technologies

related to biomass feedstock treatment, kind of gasification, gas treatment, synthesis and product upgrading. Further on, different scales are possible using different types of solid biofuels and different potential integration schemes into existing industrial facilities (e.g., pulp and paper production, crude oil refinery, petrochemicals). In Europe currently discussed BtL developments focus on FT diesel and DME (e.g., [13, 19–23]).

Considering this variety of potential technologies, the most relevant BtL production concepts in Europe have been analyzed for a reference plant size of up to 500 MW_{bf} biomass input power. This has been done to enable a qualitative comparison. Therefore the biofuel supply chains are virtually scaled. This can be realized by one or several plants. The decision whether

one 500-MW_{bf} plant or several smaller plants will be realized is taken based on recommendations given by the respective technology developer. Table 1 provides an overview about the different technologies [4].

Technical Assessment

Each of the concepts has been developed within a specific technical and economic background that leads to a specific optimization of the process conditions. Considering that fact, differences in the technical performance are observed. In order to compare the most relevant differences, a multi-criteria assessment methodology has been adapted and applied (e.g., [4, 24]). This method allows evaluating different pros and cons on (1) efficiency, (2) flexibility, and (3) industrial

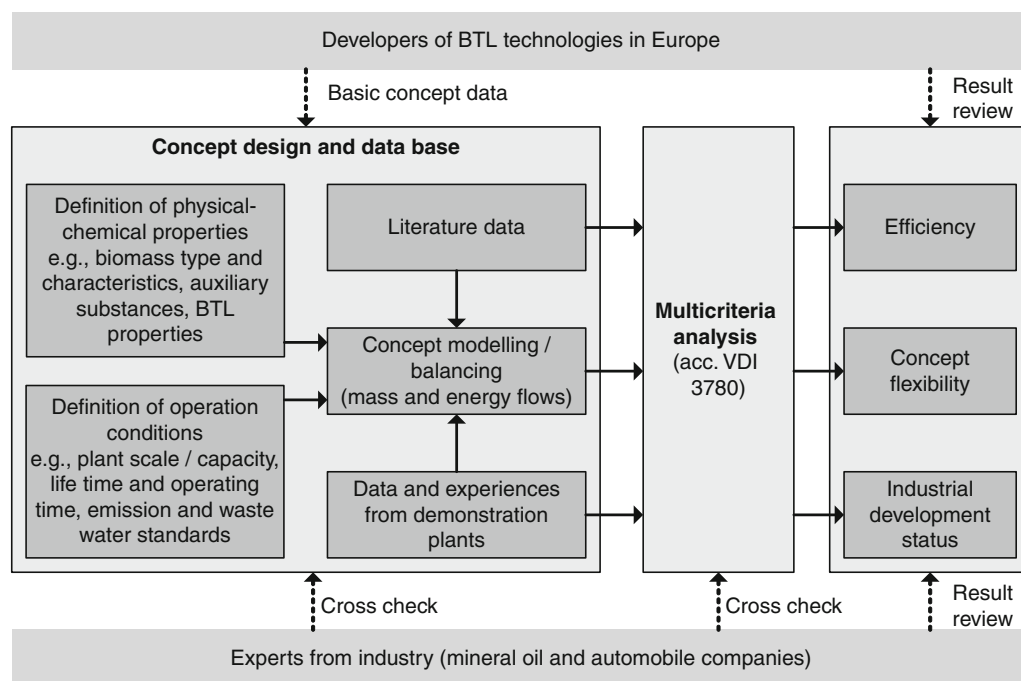
Biomass to Liquid (BtL), Concepts and Their Assessment. Table 1 Overview of assessed BtL concepts (European conditions)

Concept	1	2	3	4	5
Pretreatment					
Mechan./thermal	Drying		–	Drying + pelletizing	Drying
Thermochemical	Carbonization	Fast pyrolysis	Residue: black liquor from pulp mill ^a	–	
Location	Plant	Decentral	Plant		
Gasification	Entrained flow			Circulating fluidized bed	
	Chemical quench	Quench		Autothermal	Allothermal
Main gas cleaning/conditioning	Conventional physical absorption			Dedicated technologies	
	Selexol	Rectisol			
Synthesis (reactor, catalyst)	Tubular fixed bed reactor, Co	Slurry bubble column reactor, Co	Conventional indirect MeOH-DME	Tubular fixed bed reactor, Fe	Slurry bubble column reactor, Fe
Fuel upgrading	Distillation, hydrocracking		Distillation	External upgrading in refinery	
Main fuel product	FT diesel	FT raw product	DME	FT raw product	
By-products	Naphtha, electricity	Electricity	–	Electricity	Electricity
Plant scale ^b	Medium	Large	Medium	Medium	Small/medium
Industrial integration ^c	Stand alone/ location specific	Refinery integration	Pulp mill	Refinery upgrading	District heat and refinery

^aNo explicit thermochemical product: residue of pulp mill

^bPlant scale focused by the concept developers

^cIntegration of mass and energy flows of the BtL plant with other industrial plants/consumers



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 3
Simplified approach for the assessment of technical aspects

development status of selected BtL concepts. A simplified approach of this analysis is shown in Fig. 3. The analysis serves as a preliminary evaluation of selected questions (like a pre-feasibility study) rather than a comprehensive study.

The quality of such an assessment is limited by the quality of the data. Thus, for all concepts the most relevant parameters for indicator calculations were fixed (e.g., properties and operation conditions; Fig. 3). Data for the concept design have been taken from engineering and operating experiences of existing concepts and demonstration plants as well as GtL and CtL plants. Both methodical approach and data have been reviewed by industry [25]. It has to be noted that the data and information applied for the analysis origins from different sources (simulation, estimation, or detailed engineering) and different development status of the BtL concepts (pilot plants, laboratory experiments, or literature).

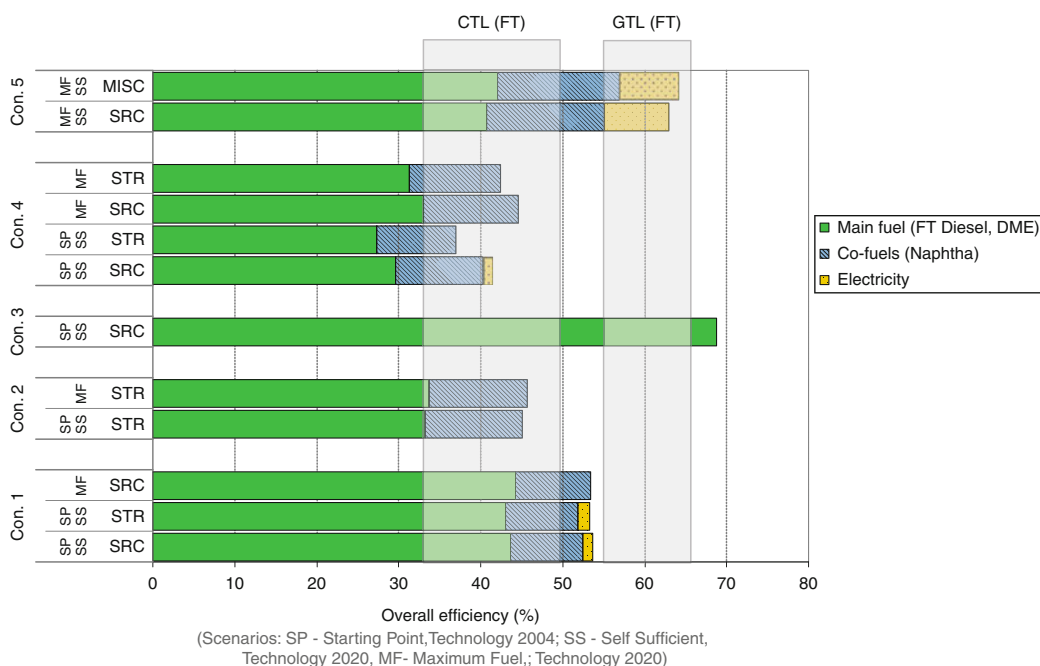
Based on this approach selected results about overall efficiencies as well as development status and R&D&D demand are summarized in the following.

Overall Efficiencies

One of the main process indicators (also with high relevance for economic and environmental issues) is the overall efficiency of the conversion plant. To calculate efficiencies different definitions are possible and legitimate in so far as coherent boundary definition is ensured (cf. [4]). Figure 4 summarizes the results of the efficiency calculation based on the so-called CHP-F method (cf. Eq. 1); the appropriate shares reflect the sum of single efficiencies, whereby the shares are representing the parts listed in the legend of the figure.

$$\eta = \frac{P_{\text{BTL}} + P_{\text{co-fuels}} + P_{\text{by-products}}}{P_{\text{input streams}}} \quad (1)$$

The CHP-F method is based considering co-fuels and by-products fuel as target power (i.e., BtL). They are useful for other applications and have not to be generated by another conversion process. Therefore by-product powers are added to the target power and equal to another.



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 4

Overall efficiencies of assessed BtL concepts and efficiency ranges of Ctl and Gtl concepts

According to that, significant differences exist between the concepts that are mainly influenced by the choice of synthesis and the integration of mass and energy flows of the BtL plant with other industrial plants/consumers (i.e., development focus/design specificity). Related to the produced fuel the production of DME as annex concept of a pulp and paper mill (concept 3) is the most efficient. This is due to a higher efficiency of the DME synthesis compared to the other synthesis routes (like Fischer–Tropsch hydrocarbon production) and the process integration of heat and power provision within a pulp and paper mill.

With today's design and technology for FT diesel production (scenario "starting point" (SP)), the highest efficiency could be achieved by the entrained flow gasification concept (concept 1). In the future, a CFB gasification concept (concept 5) shows promising opportunities to achieve one of the best diesel efficiencies. Reasons for this are optimized energetic integrations (e.g., heat or tail gas recovery) within these concepts. The technical measures shown with

these concepts are possible in principal (theoretically) but have to be confirmed within future demonstration plants.

Development Status and R&D&D Demands

In addition to efficiency and flexibility, the technical assessment of the different concepts has been extended to a preliminary qualitative evaluation of the development status of the technologies involved. This has been done based on an industrial perspective. A selection of criteria relevant to industry have been applied to analyze the overall concept, the gasification, the gas cleaning, and gas conditioning as well. The selected criteria (e.g., feedstock flexibility, scale-up issues, process design, and energy integration issues) allow addressing some of the most critical challenges in the implementation of new and complex technologies. However, they are based on qualitative assessment and should not be considered as a quantitative measurement of relative maturity of the different concepts.

Considering these indicators, there are significant differences between BtL concepts under development in Europe. This is mainly caused by the different time frames of process developments of the technology providers (i.e., more than 10 years up to only 3 years) and the development focus (i.e., from research institutes up to industrial enterprises with different departments for engineering, construction). Regardless these large differences, it has to be pointed out that none of the concepts can be called “proven technology” and can be bought off-the-shelf. Some of the concepts show a promising maturity justifying the development of a first industrial demonstration project in, e.g., 50 MW_{bf} range together with (industrial) monitoring. Others need further development and demonstration in pilot scale (<10 MW_{bf} range) also including monitoring.

Based on such an analysis and evaluation of BtL concepts in Europe, the research, demonstration, and monitoring demands have been identified as key issues (e.g., [1]). The focus of these works can be summarized as follows:

1. Feedstock flexibility. Only certain biomass feedstock have been already tested in pilot plants; for direct gasification technology the ongoing development is focused basically on woody biomass. For practical reasons (e.g., diversification of biomass origin with regard to biomass supply including storage, conditioning, and transport issues and costs) commercial plants will be adapted to few defined biomass types.
2. Gasification. Basically biomass-based CFB gasifier show a higher maturity than the EF gasifiers. Therefore they are more suited for near-future industry application. There is a further need for R&D activities in the promising and generally advantageous EF gasifier. Feedstock preparation concerns aspects like integration of feedstock with a low ash melting point into CFB gasifier (cf. concept 4, 5), thermochemical pretreatment for EF gasifier (cf., e.g., concept 2), handling of feedstock of different qualities, and feeding into pressurized reactors.
3. Gas cleaning and conditioning. Despite that some of the concepts will apply high maturity gas treatment technologies, they need to be adapted to biogenous raw gases of different gas qualities. The concepts 1–3 apply the well-adapted and

commercially proven Selexol or Rectisol unit. The other concepts include technologies that are adapted for tolerant synthesis but not yet proven commercially. This is especially true for low temperature gasifier (i.e., CFB in concept 4, 5).

4. Synthesis, raw product upgrading including refinery integration of syncrude. Basically synthesis reactors are available commercially. For concept developers large-scale commercial BtL production is expected to be realized with difficulties without the support of the mineral oil and gas industry, which has the knowledge on large-scale synthesis and product upgrading. Pilot and demonstration projects can also fail because of lacking licences for synthesis and other units.
5. Energetic integration. Since of important influence on overall plant efficiency and thus costs, process integration is one key issue for future plant developments. However, due to the dependency of local conditions at plant site this aspect is less limited by available BtL technologies rather than by identifying suitable plant locations. For instance, the high-process integration of annex plants (cf. concept 3 integrated into pulp mills) favor high efficiencies, however, only for niche applications.

In addition to that for further development of BtL plants, the most important technical issue is to develop scale-up strategies. These strategies have to include the integration of the different process steps along the whole supply chain (i.e., biomass feedstock to transportation biofuel) for demonstrating the effective process performances and reliability. Particularly concerning economic issues, industrial reliability, technical performance, and operability, respectively, have to be demonstrated. To achieve these targets, most of the technical concepts analyzed and further developed in, e.g., [4] could be useful in some context and are basically predisposed by project- and location-specific frame conditions. For each process unit (like, e.g., gasifier) industrial applications exist, however, in a different setting (e.g., in terms of feedstock, size, and final product). In order to leverage maximum learning and progress from the current pilot and demonstration activities, a detailed scientific support, modelling and monitoring in the above-mentioned fields is required.

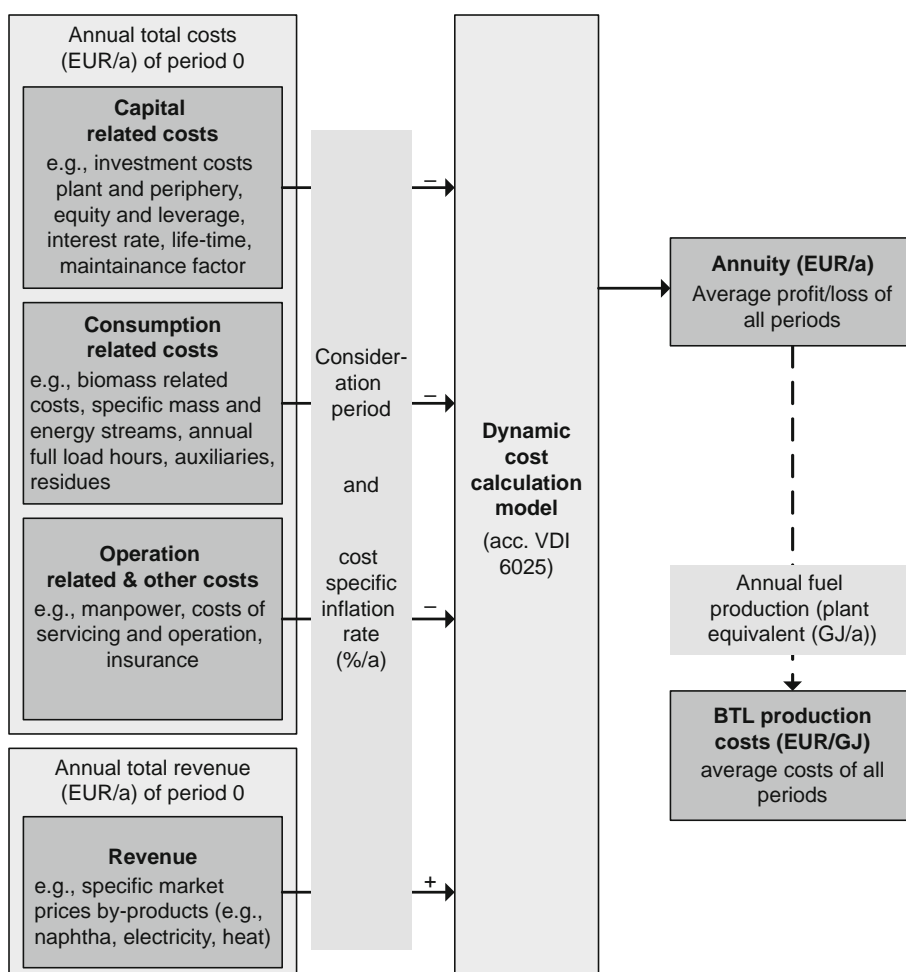
Economic Assessment

Typically, economic assessment is intended to evaluate different cost alternatives in order to identify relative advantages, to compare different options with regard to omission, and to determine important influencing factors. Especially with regard to assess biofuel production costs, dynamic partial models (e.g., based on annuity) can be favorably applied since the accuracy is higher compared to static partial models due to a periodic accounting (VDI 6025, [26]). According to this, based on the different costs and revenues the annuities can be determined. Taking the annual production rate into account, the specific BtL fuel production costs

can be calculated. The calculation approach is summarized in Fig. 5.

Knowledge or assumption of several framework parameters is required for calculating biofuel production costs at the base case 2004 (SP scenario). Listed for the various cost categories, an overview is given as follows (cf. also [27]):

- Capital-related costs. The determination of TCI costs is based on study estimation (accuracy of approx. 20–30%) including the method of additional or overhead costs. Maintenance costs are included by servicing costs.
- Consumption-related costs. For the calculation of base case BtL production costs biomass supply costs



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 5
Model for calculating BtL production costs

of 5 €/GJ_{LHV} have been used [28, 29]. Annual full load is assumed to be 8,000 h/a. Costs for process energy such as natural gas about 40 €/MWh_{NG}, for electricity about 60 €/MWh_{el} are assumed.

- Operation-related and other costs. Average personnel costs of 50,000 €/a (employee) are assumed. Servicing costs amount annually 3% of TCI. Other costs are related to TCI as well: insurance and contingencies of 1%/a, administration of 0.5%/a, and others (e.g., continuous costs, fees, or testing costs) of 0.75%/a.
- Revenues. Depending on amount and quality for by-products, revenues can be received free plant. Therefore, for naphtha about 400 €/t, for electricity 60 €/MWh_{el}, and about 30 €/MWh_{th} for heat are assumed.

Moreover, a consideration period of 20 years and an interest rate of 10% (related to leverage and equity) are assumed. The annual inflation rate amounts to 2% for capital related, other costs and revenues; for consumption and operation-related costs about 3%.

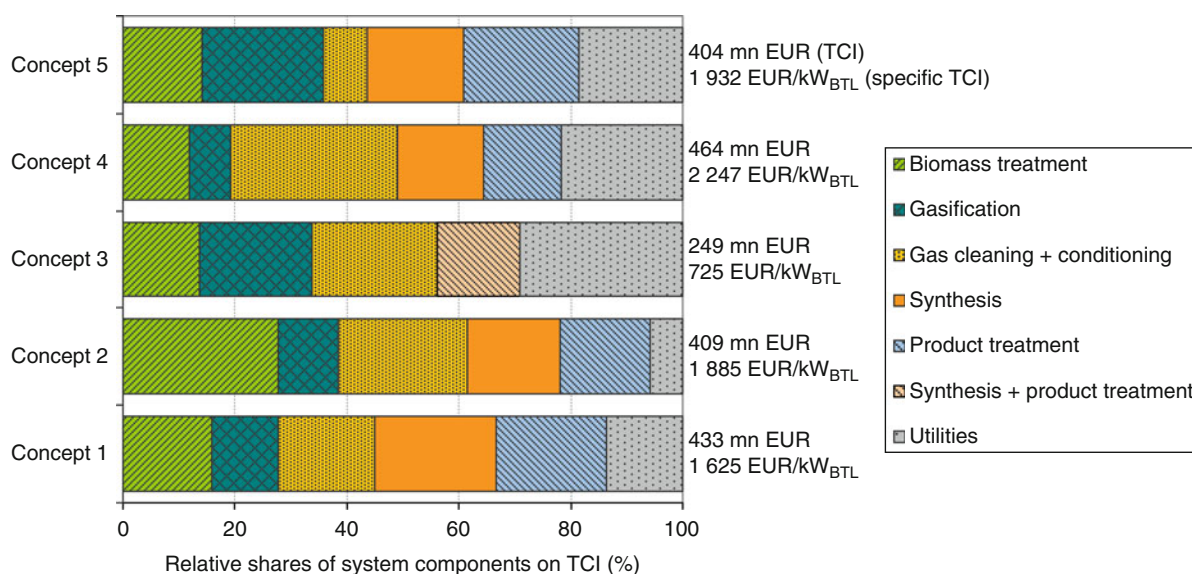
Total Capital Investment

Total capital investment (TCI) requirements of biofuel production plants are highly important with regard to financial risks and – as it is the case for more complex

biofuel concepts – regarding the biofuel production costs. The determination of TCI costs is based on study estimation (accuracy of approx. 20–30%) including the method of additional or overhead costs. According to this, plant equipment costs have been determined by up- or down-scaling (typical scale factor of approx. 0.7) of existing costs data for similar devices. Moreover, component-specific installation factors (e.g., 1.54 for large-scale to 1.66 for small-scale plants) are taken into account [14]. The investment cost figures given were calculated with particular references from literature dating from 2004 or before (e.g., [11, 14, 15, 30–33]) and for others (e.g., that are currently in pilot stage) only rough estimations of technology developers are considered. An overview of rough estimation on TCI is summarized in Fig. 6.

However, TCI for BtL plants (especially for FT fuels) are expected to be much higher compared to other existing biofuel technologies like less complex technologies for biodiesel based on transesterification or premium diesel based on hydrogenation of vegetable oils. They typically show TCI in a range of 190–470 €/kW_{biofuel} and are thus related to less capital risk than BtL [34].

With regard to economy of scale, specific TCI typically decrease with increasing plant capacity. However, there is a continuous cost increase in the engineering



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 6

Overview of TCI, specific TCI, and relative share of system components for BtL concepts (EUR = €)

and construction industries, which cannot be reflected at all. The price development of chemical plants and machinery (that also refers to biofuel production plants) is commonly indexed by means of the so-called Kölbel–Schulze methodology. According to this price index [35], the TCI for chemical plants has been increased by approx. 35% in the period from 2000 to 2007. This effect will be considered within the sensitivity analysis.

BtL Production Costs

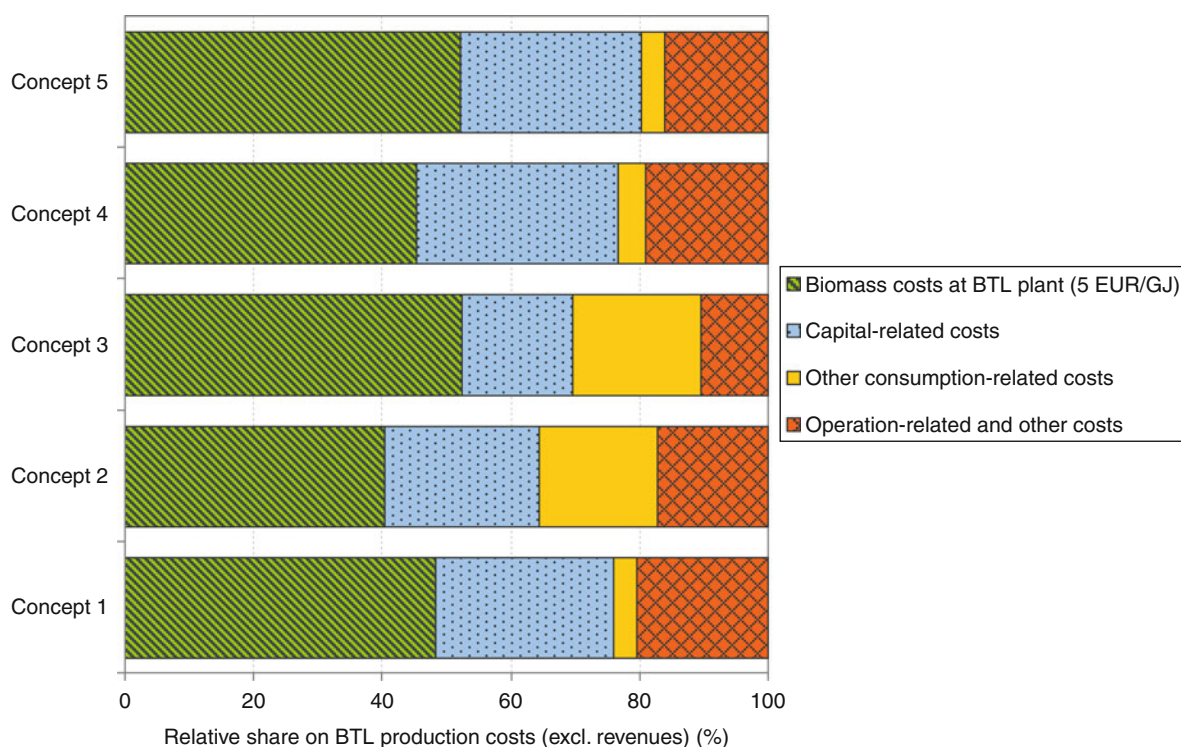
Production costs of future biofuels have been analyzed for exemplary concepts at the shown data base of the time horizon of 2004. The results are summarized in Fig. 7. As the results of the economic analysis reveal, BtL production costs show significant differences, whereby the biomass costs at plant gate are the main influencing factor. Due to this fact, plant efficiency is of strong importance. Furthermore, capital-related costs, in this relation full load hours, become relevant.

Moreover, comparing the calculated BtL production costs with consolidated results on biofuel production costs from other studies (e.g., [15, 36–42]), no significant cost reduction can be expected for FT fuels (8–47 €/GJ) and DME (13–32 €/GJ) compared to currently available biofuels such as biodiesel (4–34 €/GJ) and bioethanol (9–45 €/GJ).

Sensitivity Analyses

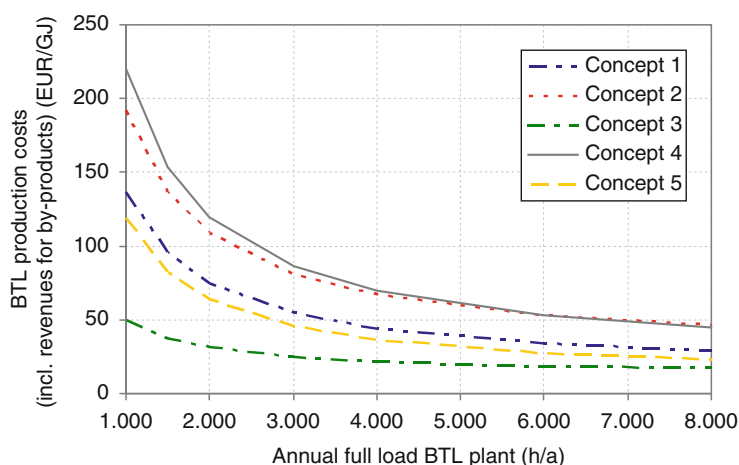
The sensitivity analyses have been carried out for the determination and optimization of influencing cost components to the total biofuel production costs for the annual full load hours of the plant, biomass costs, and TCI impact parameters. The results are briefly discussed as follows.

- Annual full load hours. For an economic and competitive operation of commercial BtL plants running hours at full load are strongly important (cf. Fig. 8). Even a reduction of annual hours of about 2,000 h/a results in an increase of BtL



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 7

Relative comparison of BtL production costs (excl. revenues for by-products) (EUR = €)



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 8

Influence of concept-specific annual full load hours ($1 \text{ €/I}_{\text{DE}} = 1 \text{ €/l}/0.0357 \text{ GJ/I}_{\text{DE}} = 28 \text{ €/GJ}_{\text{BtL}}$) ($\text{EUR} = \text{€}$)

production cost of about 9–20% compared to the base case. Following Fig. 7, BtL concepts with comparably lower fixed costs (i.e., capital- and operation-related costs) or higher consumption-related costs (incl. biomass supply costs), respectively, are less dependent on annual running hours (e.g., concept 3, 5).

- Biomass costs. As shown in Fig. 9, BtL concepts with a high biomass conversion efficiency will be able to produce BtL at favorable costs at a broader biomass costs level; e.g., to produce BtL at a cost level of up to approx. 30 €/GJ biomass costs for the concept 1 can be in a range of up to 5.5 €/GJ, for the concept 4 biomass should not cost more than 2.0 €/GJ. Nevertheless, it is expected that biofuel production costs will moderately increase in future due to rising energy prices with expected price effects for feedstock during broad implementation of biofuel strategies.
- TCI and learning curves of BtL plant. As exemplarily shown for one concept (Fig. 10), doubling of TCI will result in nearly about 50% higher BtL production costs (assumed that all other cost components will be the same). In general, it can be anticipated that costs for BtL production technologies will decrease over time because of improvements in technology and therefore annual full load. Hence, some estimates can be made using the long-term experience of similar technologies (e.g., power generation). Cost reductions of technologies

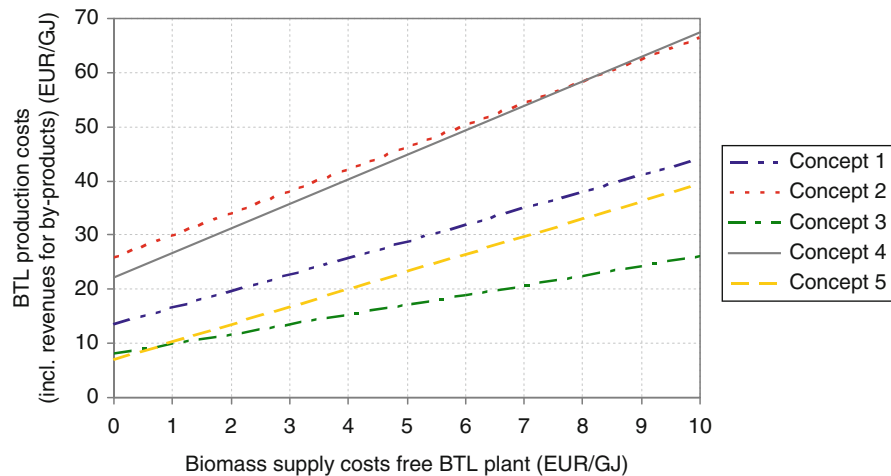
(i.e., reduction of capital investment based on cumulative installed capacity and development stage) within a certain time period (e.g., present to 2020) can be estimated using learning curves. Experiences have shown that technologies display different capital investment reduction factors with regard to their development stages (i.e., R&D, commercialization, and further improvement); the assumed digression factor for commercial BtL plants is 0.9. Taking this so-called learning curve effect into account, BtL production costs can only be slightly reduced in future.

Environmental Assessment

Assessment of BtL Concepts

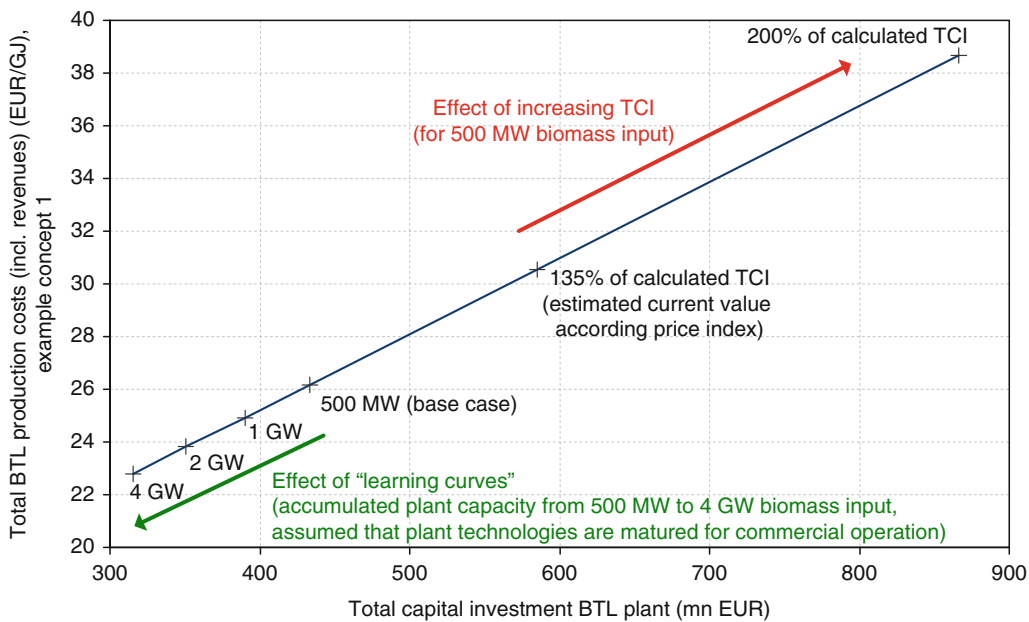
The environmental assessment of the different BtL concepts is done by means of a life cycle assessment (LCA). This takes into account not only greenhouse gas emissions or energy uses, but all types of environmental problems caused in the life cycle, e.g., eutrophication or land occupation issues.

The LCA method aims to investigate and compare environmental impacts of products or services that occur from cradle to grave. All environmental impacts caused by a product, e.g., 1 MJ of biofuel, are assessed in a standardized way. It includes all the stages during the life cycle: the production of pesticides and fertilizers, the necessary transports, the conversion of the biomass to fuel, and all emissions in the life cycle are



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 9

Influence of concept-specific efficiency and role of biomass costs to the total BtL production costs ($1 \text{ €/I}_{DE} = 1 \text{ €/I}/0.0357 \text{ GJ/I}_{DE} = 28 \text{ €/GJ}_{BtL}$) (EUR = €)



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 10

Influence of TCI and learning curves to the total BtL production costs (EUR = €)

investigated in the LCA. The method has been standardized by the International Organization for Standardization (ISO) [43].

- Goal and scope definition. The goal of the LCA is to compare different production concepts of BtL fuels (cf. Table 1) [44]. The assessment includes all

process stages from well-to-tank (WTT), i.e., biomass production and provision, BtL production, BtL distribution to end use. The reference flow describes in a physical unit the final product or service delivered by the investigated product systems. It is the appropriate unit for analyzing

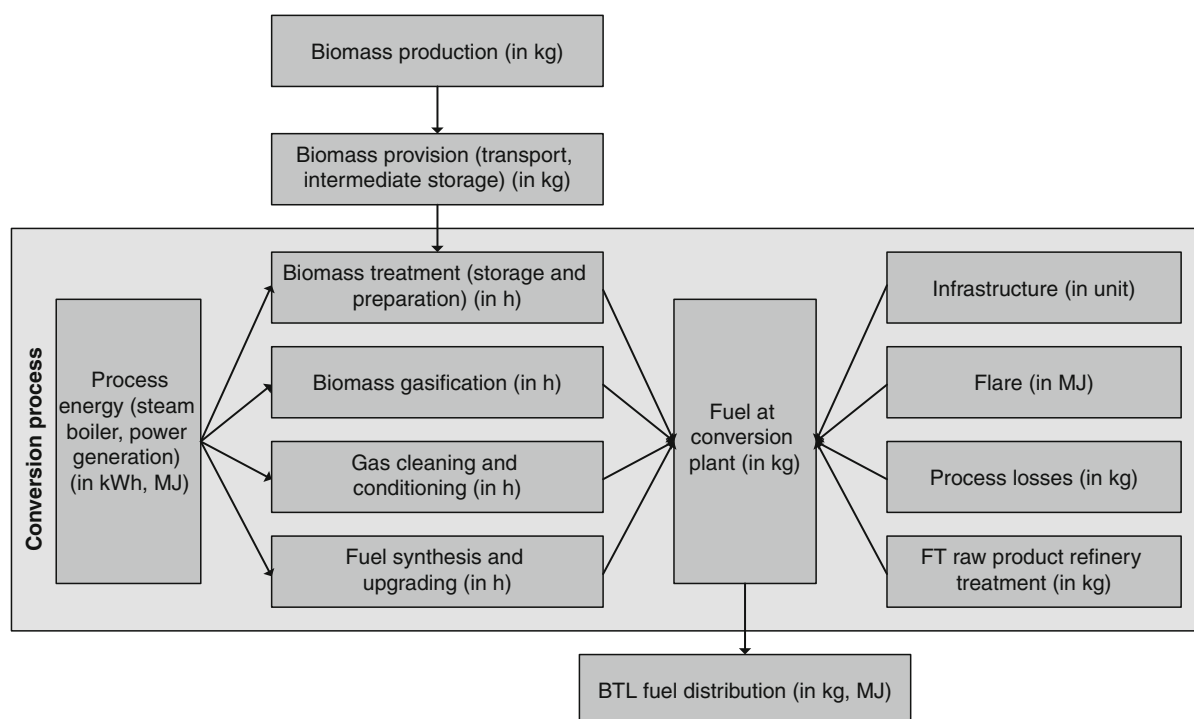
different products or production routes. Therefore, the function of interest is the supply of chemically bound energy (BtL) to powertrains. The reference flow used in the comparison of BtL fuel production routes is defined as the energy content expressed as the “lower heating value of the fuel delivered to the tank.” Figure 11 shows the major stages of the fuel production and supply part of the product system. The conversion processes are divided into different subprocesses (e.g., gasification, gas treatment, synthesis). The LCA relies on the recursively modelled background data of the ecoinvent database v2.01 [44, 45].

The LCA assigns the environmental impacts of foreseen production chains to the produced products. The attribution approach is used that aims at describing the environmentally relevant actual physical flows to and from a life cycle and its subsystems. Thus, it considers only environmental impacts of the running processes and not the impacts caused by a change from one

technology to another. Results are stable over time and resistant to changes in other parts of economy. This type of analysis does not reflect that production patterns might be changed due to a decision supported by the LCA.

There is no standardized way or best solution of how to solve problems of by-products and further functions in life cycle inventory modelling. The ISO standard leaves different choices for the problem. Depending on the solution chosen, the results of an LCA might be quite different.

In this assessment, multi-output processes are divided into subsystems (where possible). If this is not possible, the approach of allocation based on different relationship principles is used as far as possible. The allocation between wheat straw and wheat grains is based on prices. The allocation between heat and electricity in the conversion power plant is based on the exergy content. Irrespective of the allocation approach chosen, it is intended that mass balances are correct in all cases. The biomass input to the



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 11

Flowchart/subsystems of the product system of BtL fuels

conversion process is fully allocated to fuel production. No part of the biomass is allocated to the generation of heat and electricity, which might be produced as a by-product.

- Life cycle inventory analysis. The second report describes the life cycle inventory analysis (LCI) for the LCA study [46]. In this step of the LCA, data are collected for all inputs and outputs in different stages of the life cycle of BtL fuels.
- Biomass production and supply. Three types of biomass inputs are used in the conversion to BtL fuels. These are SRC (short-rotation wood such as willow-salix or poplar), MISC (miscanthus), and STR (wheat straw). The life cycle inventory data are based on regional information investigated for Northern, Eastern, Southern, and Western Europe. A critical issue in the inventory of, e.g., wheat straw is the allocation between wheat straw and wheat grain. In the base case, this allocation is made with today's market prices. This gives an allocation factor of about 10% to the produced straw (on a per kilogram basis). A sensitivity analysis is calculated based on the energy content, which leads to an allocation factor of 43% to the produced straw.
- BtL production and distribution. Data of the conversion processes were provided by the different plant developers. The data are mainly based on technical modelling of such plants, which is based on experiences and knowledge gained from the research work done in the project. The data are crosschecked as far as possible during the technical assessment of the conversion concepts [4]. Where so far no reliable first-hand information is available (e.g., emission profiles of power plants, concentration of pollutants in effluents, or the use of catalysts), assumptions are based on literature data. Thus, sometimes it is difficult to distinguish between different process routes because differences could not be investigated.

All inventory data investigated are recorded in the EcoSpold data format. The format follows the ISO-TS 14048 recommendations for data documentation and exchange formats. It can be used with all major LCA software products [47]. All background data, e.g., on

fertilizer production or agricultural machinery are based on the ecoinvent database v2.0 [45]. They were investigated according to the same methodological rules as used here. The quality of background data and foreground data is on a comparable and consistent level and all data are fully transparent.

Overall Results Following the methodical approach, the part on results focuses on the life cycle impact assessment (LCIA) and the interpretation of the life cycle assessment [48]. The data describing emissions and resource uses are calculated over the full life cycle and aggregated to the list of category indicators before interpretation.

The elementary flows from the life cycle inventory analysis are characterized according to commonly accepted methodologies. The life cycle impact assessment (LCIA) covers several impact category indicators (cf. Table 2). These indicators characterize and summarize the contribution of individual emissions or resource uses to a specific environmental problem. The higher the figure, the higher is the potential environmental impact resulting from emissions and resource uses over the life cycle of the investigated product. There is no weighting used across the category indicators. This life cycle impact assessment evaluates the use of primary energy resources, the emission of greenhouse gases, and the potential contribution of elementary flows to photochemical oxidant formation, acidification, and eutrophication. Besides the LCIA results, two cumulative results of elementary flows are presented. The water use sums up all demands of water in the life cycle including rainwater but excluding turbine water. For land competition, all surface land uses are summed up as square meter used over 1 year.

The main drivers regarding all environmental category indicators have been analyzed [44]. They can be summarized as follows:

- The major elementary flow regarding the cumulative energy demand is the energy bound in harvested biomass. Thus, the biomass production process accounts for 80–90% of the cumulative energy demand.
- Crude oil (50–60%) and natural gas use are the major contributions to abiotic depletion. The use of uranium has only a small contribution within

Biomass to Liquid (BtL), Concepts and Their Assessment. Table 2 Category indicators investigated in this assessment [49, 50]

Category indicator	Description of the problem and relevance for the processes investigated
Cumulative energy demand (CED)	The cumulative energy demand of biomass, other renewable, fossil, and nuclear energy resources is characterized and summed up with the reference unit MJ _{eq} (MJ equivalents).
Abiotic depletion potential (ADP)	Important is the use of nonrenewable energy resources. The depletion of other abiotic resources is included in this indicator as well. The use of uranium for electricity generation is included with a smaller characterization factor compared to the CED.
Global warming potential (GWP)	Contribution to the problem of climate change evaluated with the global warming potential. Main reason for promotion of BtL fuels.
Photochemical oxidation potential, non-biogenic (POCP, non-biogenic)	Evaluation of potential contribution to the formation of summer smog. The production processes and agriculture have some relevance. It has to be noted that only a small part of NMVOC gets a characterization factor according to the CML methodology. All unspecified NMVOC are not assessed. Biogenic emissions from plant growing are not evaluated, but other biogenic emission, e.g., CO from biomass burning.
Acidification potential (AP)	Emission of acid substances contributing to the formation of acid rain. Relevant are air emissions from agriculture and fuel combustion in transport processes.
Eutrophication potential (EP)	Overfertilization of rivers and lakes due to human-made emissions. High relevance for the use of fertilizers in agricultural processes.
Inventory results for resources	
Water use	Water is a scarce resource especially in Southern European countries. The indicator includes all types of water use including rainfall on the agricultural area, irrigation water, and direct uses of water in conversion processes.
Land competition	Fertile land area is the most important resource for production of biomass and there are differences between different biomass types. It is recorded in m ² /a (square meter occupied for 1 year).

this category indicator. The resource extraction takes place in many different unit processes of the life cycle.

- Fossil carbon dioxide (50–70%) and dinitrogen monoxide (20–40%) are the major elementary flows with respect to climate change. Methane from off-gases and emissions of the internal power plant in the conversion plant accounts for up to 15% of the total greenhouse gas emissions.
- A range of different substances is important with regard to the photochemical oxidation. The most important ones are sulfur dioxide, carbon monoxide, and different NMVOC. DME emissions are relevant in the fuel distribution.
- Acidification is caused by ammonia, sulfur dioxide, and nitrogen oxides in about equal shares. The emissions of acidifying substances can be attributed to the biomass production, direct air emissions of these conversion processes that release off-gases, and emissions from the internal power plant. The operation of transport devices and tractors is also an important source of such emissions.
- Eutrophication is caused by nitrates, phosphates, ammonia, and nitrogen oxides. A share of more than 50% of the release of eutrophication emissions can be attributed in most cases directly to the agricultural production process. Other important sources of emissions are the direct air emissions from the conversion process and power plant. The

production of fertilizers contributes in smaller amounts.

- The water use is fully dominated by rainwater used in agriculture. Other water uses, e.g., in the conversion plant or for irrigation are not very important.
- The results for land competition are dominated by the agricultural biomass production, which accounts for about 90% of all land uses. For the conversion routes based on straw, this share is reduced to 80%. Because of the allocation procedure, only a small part of the land used for wheat cultivating is attributed to straw. Several wood-consuming background processes, e.g., storage facilities, get a share of up to 20% in the land occupation of straw conversion routes.

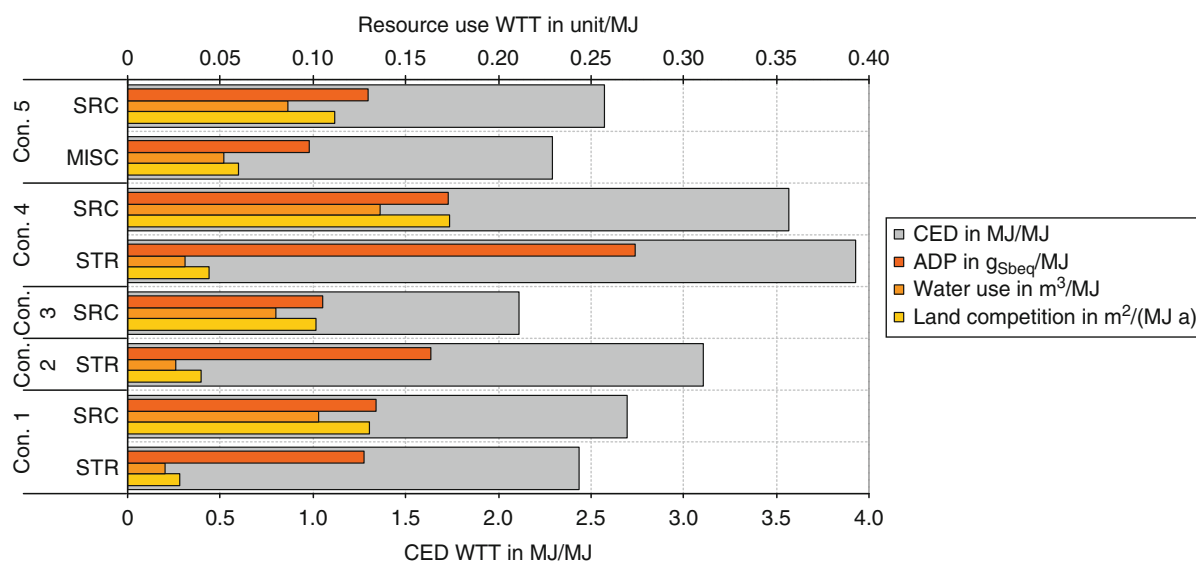
In the following, the category indicator results of different conversion concepts are compared from well to tank. They are summarized in Figs. 12 and 13. Many category indicators like acidification, eutrophication, water use, and land competition show an absolutely dominating influence of the agricultural production of biomass. Thus, the type of biomass and the conversion rate are important in the comparison.

The conversion rate plays a major role in the formation of air emissions from the conversion plant. It is assumed that the higher the conversion rate, the lower is

the share of biogenic carbon dioxide and thus also other pollutants that are released to the ambient air. Therefore, the improvement of the conversion rates and the reduction of the environmental burdens of the biomass production itself are the main drivers for further environmental improvements of the BtL chains.

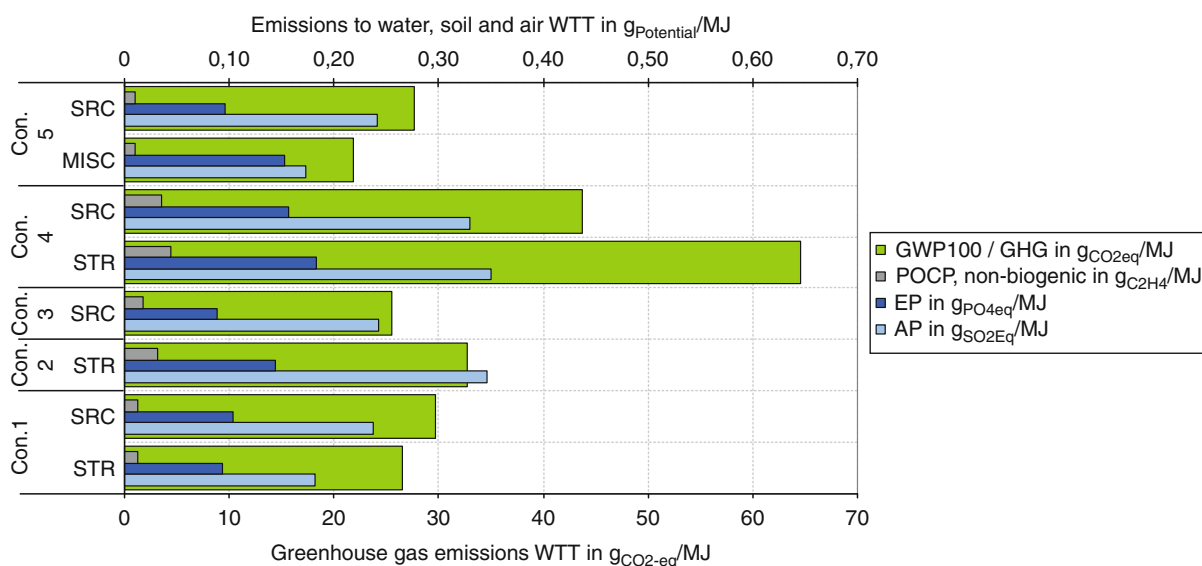
The BtL concepts 1 and 3 have the lowest environmental impacts in the assessment with regard to the environmental indicators cumulative energy demand, global warming, photochemical oxidation, acidification, eutrophication, and abiotic resource depletion. They are followed by concept 4 and 2 process. Concept 5 shows the highest environmental impacts due to a process design with a considerably high amount of electricity production and thus a lower biomass to fuel conversion rate.

In the case of the conversion of wood, concept 1 has between 15% and 30% higher impacts than concept 3 with regard to the category indicators cumulative energy demand, abiotic depletion, global warming, eutrophication, water and land use. This can mainly be explained with the higher conversion rate of the DME process. However, the concept 1 has 35% lower impacts in the category indicator photochemical oxidation, because the emissions in the DME distribution are higher. Concept 4 has more than 65% higher impacts than concepts 1 and 3. Concept 5 has a rather



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 12

Cumulative energy demand and other resource uses based on the energy content of BtL delivered to the tank



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 13

Greenhouse gas emission (global warming potential) and other emissions to water, soil, and air based on the energy content of BtL delivered to the tank

low conversion rate and thus has higher impacts in all category indicators except photochemical oxidation, which does not include biogenic emissions.

The comparison of processes based on wood or straw depends not only on the type of biomass, but also on the difference in the conversion rate. The CFB-D process based on wood performs slightly better than processes based on straw regarding the category indicators of cumulative energy demand, abiotic depletion, global warming potential, and eutrophication potential. For concept 1, the process with straw has lower environmental impacts than the conversion of wood. In the case of straw conversion, concept 1 has the lowest impacts in all category indicators followed by concept 2 and 4 process. There is only one conversion process using *Miscanthus* (concept 5). Thus, a direct comparison with other conversion concepts is not possible.

Sensitivity Results The data of biomass conversion have been investigated in detail for different subprocesses of the process. The aim was to compare also different subprocesses and to see the relative share of subprocesses in relation to the total environmental impacts.

In general, many category indicators' results of the subprocesses of the conversion process are quite

dependent on the biomass input. The share of biomass production and provision is in most cases higher than 90% with respect to the cumulative energy demand, water use, and land competition. The second most important factor is the air emissions with off-gases or due to the energy production in the on-site power plant. This is especially important for the release of substances contributing to photochemical oxidation. Thus, the subprocesses using more heat and electricity contribute more to the total environmental impacts.

The detailed analysis shows that it is difficult to compare different conversion concepts based on the detailed results of single process stages, because the allocation of environmentally relevant streams within the plant might be quite different. Thus, the importance of the different subprocesses might be distinctly different even if the overall results are quite similar.

The allocation criterion between straw and wheat grains has an important influence on the total impacts of all processes that use straw as an input. Allocation by energy content results in up to three times higher environmental impacts per MJ of fuel produced from straw as compared to allocation by actual market prices.

A sensitivity analysis of concept 5 was made. Heat and electricity produced simultaneously are accounted for as equal products to liquid fuels according to their

exergy content. The results of different category indicators are reduced by 10–30%, if the wood input for concept 5 is reduced by about 30% according to the exergy shares of fuel, heat, and electricity production.

Different improvement options are identified from an environmental point of view. The most important one is the increase of the biofuel yield from a given amount of biomass. This reduces the input of biomass and decreases the losses, e.g., in form of air pollutants or effluents. Another conclusion is to improve the environmental profile of the biomass production itself, because this analysis shows that the biomass production has a dominating influence on most of the environmental indicators. Using wastes and by-products is therefore preferable with respect to some category indicators, but not always possible. Possibilities for such an improvement have not been evaluated in detail. Detailed studies of agricultural production show that improvements are not easy to achieve. Different influencing factors, e.g., fertilizer and pesticide use, diesel consumption, and level of yields, have to be balanced out to find an optimum solution. Also the use of wood from forests, produced without using fertilizers and pesticides, might be a viable option for the provision of biomass not yet investigated.

For some processes, auxiliary inputs, e.g., quicklime, are found to be an important contribution to some category indicators. Thus, further focus should be put on reducing the necessary input. In addition, a separate refinery treatment of FT raw products can increase the environmental impacts slightly. Nutrients, which are bound in the biomass, such as phosphorous, are lost with the disposal of ashes, sludge, slag, or effluents. Recovering these nutrients and recycling them for a use in agriculture might be another option to improve the overall performance.

Comparison with Fossil Fuels

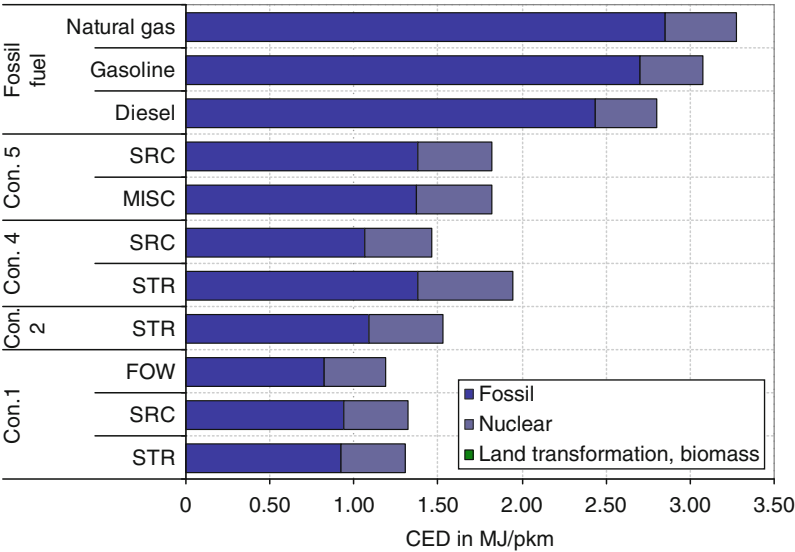
A second study has investigated the use of BtL fuels and compared it with fossil diesel [51]. The study has been elaborated as a follow-up study of a recent investigation on several types of biofuels [52, 53]. In that study the environmental impacts of several biofuel options like biogas, plant oil methyl ethers, ethanol, and methanol have been investigated from a Swiss market perspective. The study investigated mainly renewable fuels, which

are directly produced from a biomass resource by a physical, chemical, or biological process like oil pressing, chemical reaction, fermentation, or anaerobic digestion. The former study concluded that with many biofuels it would be possible to reduce the emissions of greenhouse gases. But, on the other side there are severe disadvantages regarding several other environmental problems if biofuels are compared with fossil fuels.

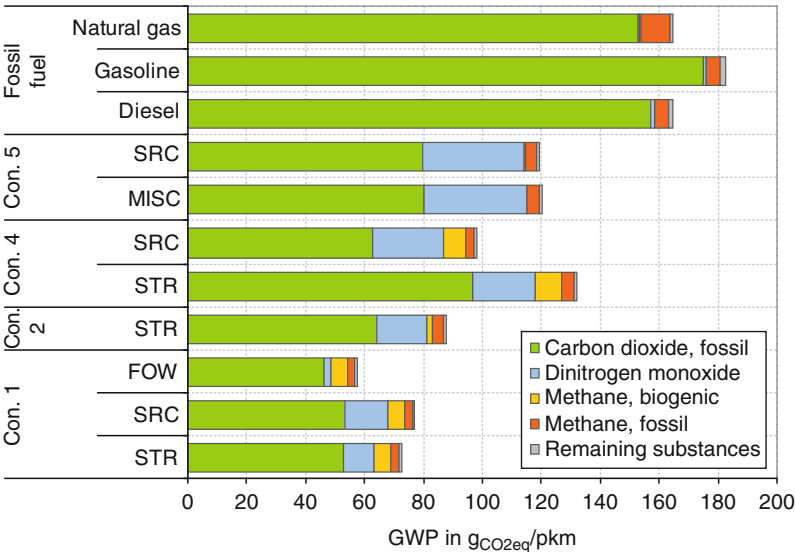
- Goal and scope definition. The goal is the investigation of the transport service provided by passenger cars and this is compared with the fossil references natural gas, diesel, and petrol. This includes the necessary infrastructure for roads and its maintenance and the production, maintenance, and disposal of cars. Thus, this is the evaluation of the full life cycle of transport services, which is also commonly referred to as “cradle to grave.”
- Life cycle inventory analysis. The inventory for fuel production is based on the data mentioned above and ecoinvent data v2.0 [48, 45]. The inventory of the fuel use emissions is based on information published by automobile manufacturers on reductions due to the use of BtL fuels (cf. Table 1, here except concept 3). Passenger cars fulfilling the EURO 3 emission standards are the basis for the comparison. The use of DME produced from black liquor was not considered in the assessment because it does not seem a realistic option for the Swiss market and it is mainly meant to be used in trucks.

The Swiss study [53] compared the environmental impacts of several biofuels with using fossil fuels (i.e., low sulfur diesel and gasoline, natural gas) in conventional cars. The authors used two single score impact assessment methods for their evaluation, namely, the Eco-indicator 99 (H, A) and the ecological scarcity 2006 method [54, 55] as well as the cumulative energy use and the global warming potential [56]. With these methods, impacts of toxic substances like pesticides are also taken into account.

Comparison of BtL Fuels with Fossil Fuels Figure 14 shows a comparison of transports with passenger cars operated with BtL fuel and fossil fuel. The comparison is presented for the use of nonrenewable energy resources. The ranking of the different types of fuels is



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 14
Nonrenewable cumulative energy demand of the transport services

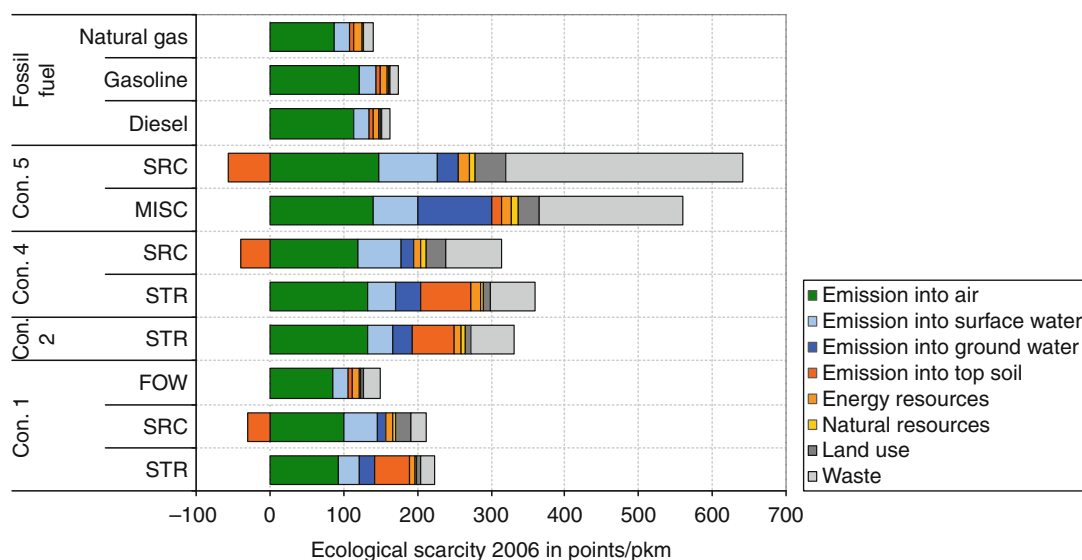


Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 15
Global warming potential of transport services

the same as already discussed on the basis of 1 MJ of fuel delivered to the tank [48]. Of interest is the difference between the transport with cars operated on BtL fuel and the reference cars operated with petrol. The inventory of a EURO 3 passenger car is taken as the baseline. The use of nonrenewable energy resources can

be reduced by 37–61% due to the use of the investigated BtL fuels.

Figure 15 compares the emission of greenhouse gases (global warming potential over a time horizon of 100 years) in the life cycle of BtL fuels and fossil fuels. The emission of greenhouse gases is reduced between



Biomass to Liquid (BtL), Concepts and Their Assessment. Figure 16
Ecological scarcity (2006) points of the transport services with different fuels

28% and 60% compared to the petrol car if BtL fuels from agricultural biomass are used. The best option with forest wood can reduce the global warming potential by even 69%.

Figure 16 shows the results with the method ecological scarcity 2006 [54]. Also here some heavy metals are removed from the agricultural soil during plant growing and thus results in the category emissions into topsoil are negative. All BtL fuels made from agricultural biomass have higher environmental impacts than the fossil reference. The emissions of nitrate are comparably higher for Miscanthus. This is the reason for the relatively higher contribution from emissions into groundwater.

For some fuels environmental impacts due to waste management are quite important. This is due to the disposal of ashes and slag from the conversion process. It might be possible to further improve the disposal or even to reuse the remaining as fertilizers in biomass production. So far such options have not been considered in the modelling of the conversion plants.

The total environmental impacts of the best option using forest wood are about the same as for the fossil reference. Thus, it is possible to produce BtL fuels competitive to fossil fuel as long as they do not use agricultural biomass such as short-rotation wood.

Comparison with Other Biofuels A comparison with other biofuels is possible based on the data investigated earlier [52, 53]. In comparison to other already available biofuels, e.g., rape methyl ether, the results are in the same order of magnitude. These results confirm the findings of a detailed LCA on existing biofuels [53]. Many biofuels derived from agricultural biomass are not preferable from an environmental point of view if the full life cycle is taken into account. But, BtL processes may also use wood from forestry or biomass residues. In comparison to short-rotation wood or other energy crops, this would substantially reduce the environmental impacts.

It is not possible to draw general conclusions for the comparison of synthetic BtL fuels with, e.g., plant oils, ethanol, or methyl ethers. For all types of renewable fuels, the used biomass type is an important factor for the environmental impacts. Thus, better and worse fuels exist in each category. Neither a general advantage nor a general disadvantage of BtL fuels compared to other biofuels is confirmed here.

The best BtL process achieves fuel yields, which allow driving about 50,000 km from the short-rotation wood grown on 1 ha. This is about the same as for sweet sorghum and in the upper range of the biofuels investigated [53]. On the other side also greenhouse gas emissions per hectare are relatively high compared to

the renewable fuels investigated in a previous study. The best option is again forest wood, but this fuel achieves slightly lower mileage per hectare than short-rotation wood. Concerning fuel yields per hectare, there is no general advantage or disadvantage compared to other types of biofuels. Again type of biomass and the large range of efficiencies lead to a wide range of possible results.

Conclusions

Synthetic fuels are of strong interest because of their designable fuel properties in order to provide premium fuels that on the one hand contribute to meet current and future exhaust emission standards and on the other hand allow the use of several raw materials for their production. BtL fuels are one option of future biofuels. There are various concepts to provide liquid synthetic biofuels based on solid biomass. So far it is open that conversion route will be implemented into the market on the background of given techno-economic constraints and necessary environmental benefits. Within this paper five different concepts for BtL provision being currently developed (i.e., FT diesel and DME) have been compared consistently by specific technical and economic criteria under European frame conditions. The results can be summarized as follows.

- The technical assessment has shown that none of the BtL concepts discussed so far has reached an industrial production level. Rather each of these concepts represents a technology leader in terms of specific aspects. An operation of the existing pilot and demonstration projects could be demonstrated in few cases and made know-how available for detailed engineering of BtL plants on the large scale. The technical measures shown for these concepts are possible in principal (theoretically) but have to be confirmed within future demonstration plants. The overall efficiencies could reach a range of 37–64%. They are mainly influenced by the choice of synthesis (here concept 3 shows favorable results) and the integration of mass and energy flows of the BtL plant (as the favorable results present for concept 1 and 5). Important issues that need to be addressed for further R&D&D covers aspects like feedstock flexibility and preparation for biomass gasification (e.g., regarding feedstock qualities and pressurized reactors) and commercial prove of gas cleaning and conditioning (e.g., for CFB gasifiers). Moreover support of the mineral oil and gas industry is important for synthesis, raw product upgrading including refinery integration of syncrude (especially for FT fuels) as well as energy integration for high efficiencies are necessary.
- From the economic assessment it can be concluded that BtL technologies are much more capital intensive than for, e.g., conventional biodiesel fuels, and thus of high capital risk concerning financing investors attractively. BtL production costs strongly depend on biomass costs and therewith on the biomass to biofuel conversion efficiency. Thus, favorable options are concepts with high conversion efficiency (e.g., concept 3), process integration (e.g., concept 1 and 5), and/or the conversion of low-cost biomass residues. Moreover – according to high TCI – parameters like capital-related costs and thus annual full load hours are of importance for an economic plant operation. Considering TCI costs reduction due to learning curves and increasing experiences for commercial technology application, the overall BtL production costs can only be reduced slightly. Thus, BtL costs are expected to be higher compared to other biofuels.
- The environmental assessment confirms that BtL fuels promise positive effects only regarding greenhouse gas emissions and use of nonrenewable energy resources, depending on their concept and frame conditions. The type of biomass input and the conversion rate to the final fuel are quite important. The emissions of greenhouse gases due to transport services can be reduced by about 60% with the best BtL processes using short-rotation wood or straw as a biomass input. This is comparable to other types of biofuels made from agricultural biomass resources. With forest wood, reductions up to 69% are possible. On the other side, there are severe disadvantages from an environmental point of view if fuels are produced from agricultural biomass. The introduction of BtL fuels made from energy crops would further increase environmental problems mainly caused due to today's agricultural practice. Emissions of substances contributing to eutrophication and acidification are much higher than those of transport services based on fossil fuels. Direct emissions of

the conversion plant and transport issues are less relevant as long as legal limits are maintained and biomass is not transported over very large distances.

Future Directions

So far all data for the conversion processes are based on modelling and not on commercial plants. Due to the variety of conversion concepts and possible biomass resources, it is not possible to make generally valid statements concerning the overall impacts of BtL fuels compared to other types of renewable or fossil fuels. All the aspects, however, especially the environmental impacts of BtL fuels have to be reevaluated when BtL fuels are introduced to the market in a commercial way. To quantify the real impacts it is necessary to know the type of biomass used and key figures of the conversion plant, in particular the conversion efficiency, amount and revenues of by-products, emissions and wastes.

In order to leverage maximum learning and progress from the current development activities for BtL, a detailed scientific support, modelling and monitoring of the overall process, and its integration into the energy system is strongly required in the years to come if BtL should contribute to cover the energy demand in a sustainable way.

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Biomass Use on a Global Scale

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Glossary

Anaerobic digestion Decomposition of biological wastes by microorganisms, usually under wet conditions, in the absence of air (oxygen), to produce biogas.

Biodiesel Biodiesel refers to a diesel-type fuel produced by transesterification of vegetable oils or animal fats.

Bioenergy Energy produced from the conversion of organic matter.

Bioethanol Alcohol with a two carbon structure and the molecular formula C_2H_5OH .

Biofuel A liquid or gaseous transport fuel produced from biomass.

Biogas A combustible gas derived from decomposing biomass under anaerobic conditions. Biogas normally consists of 50–60% methane, 25–50% carbon dioxide, and other possible elements such as nitrogen, hydrogen, or oxygen.

Biomass Non-fossilized organic material of plant and animal origin.

Bio-SNG Bio Synthetic Natural Gas is a gas that meets the quality standard of natural gas derived from syngas produced from the gasification of biomass.

Butanol Alcohol with a four carbon structure and the molecular formula C_4H_9OH .

Combustion (of biomass) The process of converting biomass fuel into heat, water, and carbon dioxide, though reaction with oxygen present in air.

Energy crops Crops grown specifically for energy. These include food crops such as corn and sugarcane, and nonfood crops such as poplar trees and switchgrass.

Fermentation Conversion of carbon-containing compounds by microorganisms for production of fuels and chemicals such as alcohols, acids, or energy-rich gases.

Fischer–Tropsch (FT) process Catalyzed chemical reaction in which syngas from gasification is converted into a liquid biofuel for gasoline, diesel, or kerosene displacement.

Gasification A thermochemical process at elevated temperature and reducing conditions to convert a solid fuel to a gaseous form (CO , H_2 , CH_4 , etc.), with char, water, and condensibles as minor products.

Hydrotreating Process which consists of the addition of pairs of hydrogen atoms to a molecule.

Lignocellulosic ethanol Ethanol produced from lignocellulosic material.

Organic Rankine cycle (ORC) A Rankine cycle is a closed circuit steam cycle to convert heat into mechanical energy in an engine. An organic Rankine Cycle uses an organic fluid with a high molecular mass instead of steam, allowing heat recovery from low temperature sources.

Pyrolysis The thermal decomposition of biomass at moderate temperatures (greater than 400°F , or 200°C) in the absence of air.

Stirling engine Closed-cycle regenerative heat engine with a gaseous working fluid. The working fluid, the gas which pushes on the piston, is permanently contained within the engine's system.

Syngas Syngas (from the contraction of synthesis gas) is a mixture of mainly carbon monoxide (CO) and hydrogen (H_2), which is the product of high temperature steam or oxygen gasification of organic material such as biomass.

Torrefaction Mild pretreatment of biomass at a temperature between 200°C and 300°C , resulting in carbonization.

Transesterification Process of exchanging the alkoxy group of an ester compound with another alcohol.

Definition of the Subject

Biomass is an extremely diverse resource that can be converted to multiple energy end uses (heat, electricity, transport fuels) through a range of mature and prospective technologies. Understanding the various options available to use biomass for energy, and their relative technical, economic, and environmental merits is important in understanding how biomass can be most effectively used. This understanding needs to be complemented by an understanding of the drivers (e.g., competing technologies, economic value, relative environmental benefits) for using biomass in different applications, and how these may change in the future.

This chapter describes the different ways in which biomass can be used to produce heat, electricity, and transport fuels, covering a range of feedstock, conversion technologies, and intermediate products, and discusses the current and prospective use of biomass in different applications.

Introduction

Biomass can be broadly defined as any non-fossilized organic material of plant and animal origin. A range of biomass products can be used for energy, including products and by-products from forestry, agriculture and aquaculture, as well as a range of agricultural, industrial, and municipal residues and wastes.

Biomass is the oldest fuel used by mankind and has been its main source of energy for cooking and keeping warm from the dawn of civilization to the industrial revolution [1]. Until the eighteenth century, humans were almost completely reliant on wood and charcoal for all of their energy needs, and it was not until the early 1800s that easily accessible coal became more prevalent as it drove Europe's industrial revolution. Over the last century, biomass has been supplanted by higher energy density, easier to handle and cheaper fossil fuels such as coal, oil, and gas.

However, while fossil fuel has mostly replaced the use of biomass, it still accounts for some 50 EJ per year globally, which represents roughly 10% of global annual primary energy consumption. While it represents a mere 3% of primary energy in industrialized countries, it accounts for 22% of the primary energy mix in developing countries, where it contributes largely to domestic heating and cooking, mostly in simple inefficient stoves. Least developed countries still rely on biomass for over 90% for their energy needs [2, 3].

At present, forestry, agricultural, and municipal residues and wastes are the main feedstocks for producing heat and electricity from biomass. In addition, a small share of sugar, grain, and vegetable oil crops are used as feedstocks for the production of liquid biofuels.

The biomass resource base is potentially large, and so are the opportunities for its increased use in different energy segments in both industrialized and developing countries. There is significant potential to expand biomass use by tapping the large volumes of

unused residues and wastes. The use of conventional crops for energy use can also be expanded, with careful consideration of land availability and food demand. In the medium term, lignocellulosic crops (both herbaceous and woody) could be produced on marginal, degraded, and surplus agricultural lands and provide the bulk of the biomass resource. In the longer term, aquatic biomass (algae) could also make a significant contribution.

Over the last 3 decades, issues of energy security, increasing prices of fossil fuels, and global warming have triggered a renewed interest in biomass for the production of heat, electricity, and transport fuels. Many countries have introduced policies to support bioenergy, not least as a means of diversifying their agricultural sectors, which has stimulated sustained growth in the sector. This has been accompanied by significant developments in conversion processes, with many technologies introduced in the market and several cleaner, more efficient technologies, capable of producing a broader range of products, at the research, development, and demonstration stage. Bioenergy has become increasingly diversified in terms of final uses, and in terms of resources, with new conversion technologies being developed to account for the varied physical nature and chemical composition of the feedstocks available, as well as the energy service required. There is also growing interest and research in the production of chemicals from biomass, possibly in conjunction with the production of energy. The multifunctional role of biomass, in terms of both the products and services it might provide, offers an opportunity to generate value beyond energy products.

Projected world primary energy demand by 2050 is expected to be in the range of 600–1,000 EJ (compared to about 500 EJ in 2008). Scenarios looking at the penetration of different low-carbon energy sources indicate that future demand for bioenergy could be up to 250 EJ/year [2]. This projected demand falls well within the estimates of sustainable biomass supply potential, so it is reasonable to assume that biomass could sustainably contribute between a quarter and a third of the future global energy mix. The contribution from bioenergy that is actually realized will depend on the cost competitiveness of bioenergy and on future policy frameworks, such as greenhouse gas emission reduction targets.

Biomass is currently the largest global contributor of renewable energy in developed and developing countries, and has significant potential to expand in the production of heat, electricity, and fuels for transport. Further deployment of bioenergy, if carefully managed, could provide an even larger contribution to global primary energy supply; significant reductions in greenhouse gas emissions, and potentially other environmental benefits; improvements in energy security and trade balances, by substituting imported fossil fuels with domestic biomass; and opportunities for economic and social development in rural communities.

Bioenergy Routes to Different End Uses

There are many bioenergy routes that can be used to convert raw biomass feedstock into a final energy product. Several conversion technologies have been developed that are adapted to the different physical nature and chemical composition of the feedstock, and to the energy service required (heat, power, transport fuel). Biomass upgrading technologies (e.g., pelletization, torrefaction, pyrolysis) are also available and being developed to convert bulky raw biomass into denser and more practical energy carriers, thereby enabling more efficient transport, storage, and convenient use in subsequent conversion processes.

The production of heat by the direct combustion of biomass is the leading bioenergy application throughout the world and is often cost-competitive with fossil fuel alternatives. Technologies range from rudimentary stoves to sophisticated modern boilers. For a more valuable and efficient use of the biomass resource, modern, large-scale heat applications are often combined with electricity production in combined heat and power (CHP) systems.

Different technologies exist or are being developed to produce electricity from biomass. Co-combustion (also called co-firing) of biomass in coal-based power plants is the lowest cost option for solid biomass conversion to electricity. Dedicated biomass combustion plants, including MSW combustion plants, are also in successful commercial operation, and many are integrated with industrial or district heating CHP facilities. Anaerobic digestion is well suited for producing

electricity and heat from wet organic materials, via the production of biogas. All these technologies are well established and commercially available. Gasification technology promises greater efficiency, better economics at both small and large scale and lower emissions compared with other biomass-based power generation options. However, reliable and cost-effective operation needs to be more widely demonstrated. Other technologies (such as Organic Rankine Cycle and Stirling engines combined with combustion systems) are currently in the demonstration stage and could prove economically viable in a range of small-scale applications, especially for CHP.

In the transport sector, biofuels are widely deployed in several countries – mainly bioethanol from starch and sugar crops and biodiesel from oil crops and residual oils and fats. Their production costs vary significantly depending on the feedstock used (and their volatile prices), and on the scale of the plant. The potential for further deploying these biofuels is high, subject to sustainability criteria, including sustainable land use criteria, being met. Methane derived from biogas is also used in several countries (e.g., Sweden), mainly as a fuel for vehicle fleets, such as municipal buses. Many other biofuel routes are under investigation or being demonstrated based on a wide range of feedstocks (different types of residues and wastes and novel crops) and on biological and thermochemical conversion routes. These biofuel routes could lead to a wider range of fuels which could more easily displace greater quantities of fossil fuels.

Further development of bioenergy technologies is needed mainly to improve the efficiency, reliability, and sustainability of bioenergy chains. In the heat sector, improvement could lead to cleaner, more reliable systems linked to higher quality fuel supplies such as pellets. In the electricity sector, the development of smaller cost-effective electricity or CHP systems could better match local resource availability. In the transport sector, improvements could lead to a wider range of higher quality and more sustainable biofuels, expanding their use across different transport sectors (e.g., aviation). Ultimately, bioenergy production may increasingly occur in biorefineries where transport biofuels, power, heat, chemicals, and other marketable products could all be coproduced from a mix of biomass feedstocks.

Combustion

Combustion is the simplest means of generating heat from relatively dry biomass. Technologies range from open fires and simple stoves rated at a few kW (3–50 kW) to sophisticated installations that combine heat and electricity production (CHP) which can service the needs of an entire community or industrial complex, to large plants of hundreds of megawatt capacity.

Burning biomass in an open fire has a low efficiency (~10–15%) and, in developing countries, where this is the primary source of heat for cooking, there have been major efforts to replace open hearths with simple stoves in order to conserve limited supplies of fuel and improve living conditions [4]. In industrialized countries, there is also a major market for biomass for domestic heating. Modern domestic biomass boilers can provide efficiencies of 70–90% and may include automated fuel feed, catalytic gas cleaning, and increasingly make use of standardized fuel such as pellets [5]. Biomass heating is well developed in European countries with good resource availability. In Sweden, in particular, a large and growing market has developed for biomass pellets, which are fired in automated systems [5].

Pellets are more expensive than the wood chips from which they are derived due to the processing. But, they have a number of advantages: they offer greater energy density, are comparatively easy to transport and have lower moisture content (below 8%) compared to wood chips. Pellets can provide a uniform product, resulting in reliable and consistent performance when burnt. This uniformity is defined within product standards, which can also prove important in facilitating the trade of biomass feedstocks [6].

Domestic heat may also be provided by district heating, where biomass is burnt in a large-scale facility and the heat distributed via a network of pipes. In general, the bigger the combustion plant the lower the capital cost per unit energy supplied, and the greater the thermal efficiency [7]. Larger facilities can also accommodate more easily the use of lower quality or contaminated biomass (e.g., waste derived fuels). These fuels are lower cost but may necessitate pretreatment or flue-gas cleaning that are generally only economically viable at a larger scale [7].

While domestic installations produce low-grade heat ($<100^{\circ}\text{C}$), large boilers produce high-pressure steam that can be used to generate electricity via steam cycles before residual heat is distributed. Such combined heat and power (CHP) systems can be very efficient (60–90%), but for maximum efficiency, they require large and stable heat loads. They are therefore economic in colder climates where district heating is installed, or where there is an industrial heat demand. Heat may also be used to provide chilling via adsorption chillers, which when combined with the supply of electricity and heat is known as tri-generation [8]. In the lower capacity range, the Stirling Engine (10–100 kW_e) and the Organic Rankine Cycle (ORC) (50–2,000 kW_e) are suitable technologies for distributed cogeneration.

A boiler combined with a steam cycle is currently the cheapest and most reliable route to produce power from biomass. While there are many relatively small-scale plants (e.g., 5–10 MW_e) that use low-cost sources of biomass local to them, the importance of economies of scale for steam cycle plants means that dedicated biomass power plants will need to be of a certain size to be economically viable (e.g., >30 MW_e), depending on the cost of biomass. The size of a plant is also generally limited by the availability of biomass or the cost of transporting biomass to it. But, the development of biomass trade is facilitating the development of larger-scale biomass power plants of hundreds of MW, generally located in port areas where biomass can be shipped in at relatively low cost.

The co-combustion of biomass with fossil fuels for heat and power production can be relevant to all scales of operation. Biomass co-firing activities have expanded rapidly in recent years, particularly in Northern Europe, and the most popular approach has involved the direct co-firing of solid biomass with coal in existing large power station boilers. This has proved to be the most cost-effective and efficient large-scale means of converting biomass to electricity, because of the scale and infrastructure associated with coal plants.

One of the largest, most advanced, and most efficient biomass CHP plants in the world is the Igelsta plant in Södertälje, near Stockholm, Sweden [9]. Commissioned in March 2010, the plant produces 200 MW of heat and 85 MW of electricity, sufficient

to heat around 50,000 homes and provide power for around 100,000 homes.

The fuel used in the Igelsta plant is a combination of wood chips from forest residues (75%) and solid recovered fuels (25%). When running at full capacity, the plant uses approx. 17,000 t of fuel per week. Keeping the plant supplied is a major logistical operation and requires approx. 200 ship-loads, 200 train deliveries, and 12,000 road shipments per year. Wood chips from forestry operations are transported by road, rail, and boat from all over Sweden and neighboring Baltic countries. The recovered fuels include scrap paper, wood, and plastic that is not suitable for recycling and is sourced from offices, shops, and industries in the Stockholm region. Pelletized waste from similar sources is imported by boat from Germany and the Netherlands. Also imported is over 100,000 t of waste wood from Norway, Belgium, and the UK. The municipality that owns the plant considers that such fuel flexibility will be critical as competition for biomass increases.

The combustion technology used at Igelsta is a circulating fluidized bed boiler, incorporating state of the art flue-gas cleaning. The heat it produces is used to raise steam: used first for electricity production (85 MW) and then to deliver low-grade heat to the local district heating network (140 MW). By condensing the steam in the flue gas, the plant is able to deliver an additional 60 MW heat to the heating network, and this gives the combined system an overall efficiency in excess of 90%.

Gasification

Gasification involves the partial oxidation of dry biomass at high temperatures ($>500^{\circ}\text{C}$) and produces a combustible mixture of carbon monoxide and hydrogen, along with some methane, carbon dioxide, water, and small amounts of nitrogen and heavier hydrocarbons (tar) [10].

Heat production using small gasifiers is commercially established with gasification-boiler systems predominantly used to retrofit natural gas or heating-oil boilers at industrial sites that have easy access to woody residues as fuel, such as wood manufacturing sites. The systems typically produce space heat, and/or process heat or steam and can also be combined with downstream equipment such as absorption chillers and

steam turbines to produce cooling and electricity, respectively [10].

Small- and large-scale gasifier-boiler systems have been developed to supply heat into district heating networks. In Finland, “Bioneer” gasifiers, with an output approximately 5 MW_{th}, were commercialized in the 1980s (following on from a research program initiated during the 1970s), and were coupled to district heating boilers, but faced stiff competition from simple combustion technologies [115, 11]. Also in Finland, a gasifier was built in Lahti in 1997 to provide low-calorific value gas to an existing pulverized coal boiler. This gasifier has a design capacity of 45–70 MW_{th}, and the feedstock is 50% biomass and 50% recycled wood and refuse derived fuel, although demolition wood and shredded tires have also been used.

A potentially interesting future option for delivering renewable heat is to produce a synthetic natural gas from biomass (Bio-SNG) by catalytically converting gas produced from the gasification of the biomass into methane and upgrading (the gas may also need to be enriched to ensure that the calorific value meets the specification required by the network) it to remove water and CO₂. This gas can then be injected into national gas networks and used in domestic and industrial boilers. The technology for producing SNG from coal is mature, and a commercial scale gasifier has operated in North Dakota since 1984. Production from biomass, however, is still at a pre-commercial stage. Interest is growing, however, and large-scale demonstration projects are currently being planned in the Netherlands (10 MW_{th}) and Gothenburg, Sweden (approx. 30 MW_{th}) [12, 13].

Cogeneration of heat and power on a small scale has been attempted using fixed bed gasifiers coupled to modified diesel engines (100–200 kW_e). The principle motivation has been to provide small-scale electricity supply to rural locations in developing countries, though several other demonstration projects have been developed elsewhere (e.g., in Europe and the USA), with the aim to develop a low-cost small-scale electricity generation system. In India, it has been reported that 1,844 biomass gasifier systems with an aggregate capacity of 62 MW_e were deployed by 2004 [14]. Costs, maintenance, and automation requirements have hindered the deployment of such systems outside a developing country context.

A plant in Güssing, Austria, provides a larger-scale example of a gasifier coupled with a gas engine to produce electricity and provide heat to the local district heating system. This plant runs on wood chips from the local area and has a fuel capacity of 8 MW and an electrical output of about 2 MW_e [15]. In 2010, total operating hours since commissioning in 2002 were reported as 43,000 h for the engine and 53,000 h for the gasifier, making this one of the most successful biomass gasification demonstrations [16].

Combining intermediate scale (approx. 10 MW_{th}) gasification with a combined cycle gas turbine was the focus of significant attention in the 1990s. This concept (known as Biomass Integrated Gasification Combined Cycle (BIGCC)) is theoretically appealing because it could provide a greater ratio of electricity to heat and allow for larger-scale electricity generation from gasification systems. Demonstration projects were initiated and undertaken in Sweden, the UK, and the USA, but the technology has proven difficult to commercialize so far: costs remain very high and cleaning the gas to the specification required by the turbine has proved more difficult than expected. Thus far, the technology as a whole remains pre-commercial [5].

Gasification is an important component of several of the proposed new biofuel production routes, such as catalytic routes to diesel, gasoline, naphtha, methanol, ethanol and other alcohols, and syngas fermentation routes to ethanol. Many of the component technologies for some of these routes, such as feedstock preparation, gasification, and Fischer–Tropsch or methanol synthesis are commercially viable or technically mature for other applications. However, the systems as a whole are at the early demonstration stage worldwide, with further development and learning needed to achieve commercially viable fuel production [10].

Anaerobic Digestion

Wet and green biomass can be used to produce biomethane via anaerobic digestion (AD). This technology is fully mature and has been commercially applied at scales ranging from household digesters (approx. 2 m³) to large municipal waste treatment facilities. All types of biomass can be used as substrates for biogas production as long as they contain a high proportion of carbohydrates, proteins, fats, cellulose,

and hemicelluloses. Highly lignified biomass – e.g., wood – is not suitable without pretreatment due to the fact that lignin cannot be anaerobically decomposed by existing bacteria [17].

Anaerobic digestion produces biogas and digestate. The digestate comprises residual indigestible material (e.g., lignin) and dead microorganisms; it contains valuable plant nutrients like nitrogen and potassium and can be used as a fertilizer and soil conditioner [18]. The biogas is a mixture of methane (ca. 60%), carbon dioxide (ca. 40%), and trace contaminant gases such as hydrogen sulfide; it can be burnt to provide heat, electricity, or both. The biogas can also be stripped of the carbon dioxide, and the methane purified and compressed or liquefied to be used as a fuel for vehicles. Alternatively, the methane can also be injected into the natural gas grid, and several countries, such as Germany, Sweden, and Switzerland, have defined quality standards for biogas injection into the grid [19].

The world's biggest biogas producer is China, where, in 2007, there were an estimated 26.5 million biogas plants, with a gas output of 10.5 billion m³ [20]. The construction of biogas digesters has also been a key part of the development of renewable energy sources in India where an estimated 3.9 million digesters were installed by 2006; the vast majority of these are family-scale digesters based on cow dung and used for producing fuel for cooking [21].

In Europe, biogas generation for electricity production has grown rapidly. In early 2010, about 5,900 biogas plants with an installed electrical capacity of 2,300 MW_e were operational, and it is predicted that more than 3,000 biogas plants with an electrical capacity of more than 1,700 MW_e will be constructed between 2009 and 2013. Germany is the country with the largest installed capacity, but an increasing number of EU Member States are creating the necessary regulatory frameworks to encourage growth of the national biogas industries [22]. Germany also hosts the world's largest biogas plant at Güstrow. This plant started in 2009 and has a capacity of 50 MW_{th}. The plant can digest 450,000 t of biomass (maize, grain, and silage) per year. The gas is upgraded and injected into the gas grid, and the digestate is returned to the fields [23].

Anaerobic digestion is little developed in the USA, and as of 2010, there were only 151 digesters

with a capacity of about 37 MW_e (and 6 MW_{th}). The majority (80%) of these plants are located at dairy farms [24].

Fermentation and Other Microbial Routes

Sugar from crops such as sugarcane and sugar beet is easily fermented to ethanol using yeast in a process known for millennia by mankind. Starches from crops such as corn and wheat can also be easily converted to sugars that can then be fermented to ethanol. Ethanol production using fermentation is the cheapest and most commonly used production route for biofuels for transport. The main producing countries are the USA, based on corn/maize, and Brazil, based on sugarcane. There are around 200 ethanol plants in the USA for a total production capacity of around 50 billion liters, and around 400 plants in Brazil for a total production capacity of around 25 billion liters. In Brazil, ethanol plants coproduce ethanol and sugar for the food market. Corn ethanol plants coproduce dry distillers grains and solubles (DDGS) that are used as animal feed.

Cellulose and hemicellulose, which together with lignin make up most forms of plant biomass, can be broken down into sugars, which can then be fermented into ethanol. Lignocellulosic materials, such as straw, grass, and wood, are more difficult to break down than starch, and therefore require more complex pretreatment to release the constituent sugars from the biomass. Lignocellulosic ethanol conversion technology is at the demonstration stage, with demonstration plants being developed globally. The USA is where most lignocellulosic ethanol activity is centered, and 28 projects are under development.

Sugars can also be converted by microbial processes into higher alcohols, e.g., butanol, and into longer hydrocarbon chains, that could replace gasoline, diesel, and jet fuel. Microbial butanol production is commercial, but the majority of alternative processes are at an early stage of development.

Transesterification and Hydrotreating

Vegetable oils are converted to biodiesel by reacting them with an alcohol in the presence of a base or acid catalyst, a process known as transesterification, which improves the fuel properties of the biodiesel compared

to a straight vegetable oil. Biodiesel is produced globally by transesterifying a range of vegetable oils such as rapeseed, sunflower, soy and palm oil, as well as used cooking oils and animal fats. Most biodiesel production occurs in Europe, with a production capacity of around 20 million tons.

An alternative commercial process for the production of renewable diesel is hydrogenation, which consists of reacting the vegetable oil with hydrogen in the presence of a catalyst. It produces a renewable diesel of superior quality (with higher blending potential) to that obtained via transesterification, and could also be used to produce renewable jet fuel. However, hydrogenation is a more complex process that requires large-scale installations, and as such, is less deployed to date, with a few plants in Europe and South-East Asia.

Alternative sources of oils to conventional oil crops are being developed which could extend vegetable oil production to areas less suitable or not suitable for food crops and which would not compete with them. Examples of these alternative sources of oil are crops like *jatropha* and algae.

Pyrolysis and Other Thermochemical Processes

Pyrolysis is the controlled thermal decomposition of solid biomass occurring at around 500°C in the absence of oxygen (anaerobic environment) and produces a liquid bio-oil, gas (syngas), and charcoal (biochar) mix. Bio-oils can also be produced by liquefaction in the presence of water, and possibly additional solvents (e.g., methanol), at high pressure (120–200 bar) and relatively mild temperatures (300–400°C) in a process is known as hydrothermal upgrading (HTU). One attractive feature of this process is that wet biomass can be used directly and yields a bio-oil that is less soluble in water.

Compared to raw solid biomass, bio-oil should be cheaper to handle, store, and transport. Also, the energy density (per unit volume) of bio-oil is higher than that of pellets or torrefied biomass, which gives it a competitive advantage in terms of transport cost.

Bio-oil could be upgraded and used as a transport fuel, providing an efficient route to fuels that could be closely integrated with a petroleum infrastructure. It could also be used as fuel for heating and electricity generation, or to produce valuable chemicals.

In spite of these advantages and recent advances, these technologies are at the demonstration stage. Only a few successful pyrolysis demonstration units have been realized (e.g., in Finland and Canada), and both economic and technical issues around quality, consistency, and long-term stability of the bio-oil, which tends to degrade over time, remain to be addressed.

Overview of Current and Future Biomass Use

The predominant use of biomass today consists of fuel wood used in noncommercial applications, in simple inefficient stoves for domestic heating and cooking in developing countries, where biomass contributes some 22% to the total primary energy mix. The IEA [3] estimates that about 2.7 billion people will still be dependent on biomass for cooking in 2030. There is significant scope to improve the efficiency of this use and its environmental performance, and thereby help reduce biomass consumption and related impacts.

In industrialized countries, the total contribution of modern biomass is on average only about 3% of total primary energy and consists mostly of heat-only and heat and power applications [2]. Current heat and electricity market segments which are experiencing growth include domestic heat supply (e.g., pellet boilers), large-scale industrial and community CHP generation (particularly where low-cost feedstocks such as forest residues, bagasse, MSW, etc., are available), and co-firing in large coal-based power plants. The deployment of dedicated electricity plants has been mainly confined to low-cost feedstocks in relatively small-scale applications, such as the use of biogas and landfill gas from waste treatment. However, several relatively large-scale dedicated plants (of up to a few hundred megawatts) fuelled with wood chips are being developed around the world, generally because of a strengthening in national renewable energy policies.

Transport biofuels are currently the fastest growing bioenergy sector, receiving a lot of public attention. They represent only 1.5% of total road transport fuel consumption and only 2% of total bioenergy, but are expected to play an increasing role in meeting the demand for road transport fuel [2].

Overall, world primary energy demand from biomass and waste is expected to grow from 1,176 Mtoe (1 Mtoe = 0.042 EJ) in 2007 to 1,604 Mtoe in

2030 in the IEA's Reference Scenario [3], representing 10% of total primary energy. Biomass use for power generation goes from 84 Mtoe in 2007 to 257 Mtoe in 2030 (4% of electricity), corresponding to 259–839 TWh (1 TWh = 3.6 PJ) of electricity produced and an installed capacity of 46–146 GW. Biomass use for biofuels goes from 34 Mtoe in 2007 to 133 Mtoe in 2030 (4% of transport fuels).

In the IEA's 450 Scenario (where CO₂ in the atmosphere is stabilized at 450 ppm in the period to 2050), biomass use is higher than in the Reference Scenario in 2030 (350 Mtoe higher), representing 16% of total primary energy demand. Major increases in the use of biomass are predicted in all sectors, with use in combined heat and power production and in electricity-only power plants up by 67% (172 Mtoe) compared to the Reference Scenario in 2030 (contributing 5% of electricity), and the contribution of biofuels more than doubling, reaching 278 Mtoe in 2030 (contributing 9% of energy for transport). The eightfold increase over the 2010–2030 period is estimated to occur mainly in those regions that already have the strongest support for biofuels, led by the USA and followed by the European Union, Brazil, and China. Biofuels also make a significant appearance in aviation, with volumes reaching 42 Mtoe globally by 2030 at a global blending ratio of 15% (compared to a mere 1% in the Reference Scenario).

Biomass Use for Heat and Electricity

Biomass can be used to generate heat at all scales required, ranging from a single household to a large industrial complex, and using all types of biomass. Biomass-to-heat systems are commercial, and in many cases, they are also cost-competitive with their fossil fuel alternatives, particularly in locations not connected to a natural gas grid [2]. The principal technologies used to deliver modern biomass heat are combustion, gasification, and digestion.

Globally, around 2.6 billion people are still reliant on traditional uses of biomass and burn wood, straw, charcoal, and dung to provide basic energy services such as cooking and heating [25]. This use is dominant in rural areas of developing countries and is associated with poverty and deforestation [26, 27]. Traditional conversion technologies, such as simple combustion

in open hearths, also tend to be inefficient and contribute to indoor air pollution which can damage health [28]. Using biomass in this way accounts for about 13% of global final energy consumption and about 87% (39 EJ) of global bioenergy [2], though the extent of biomass use is difficult to estimate accurately.

Biomass is also extensively used for domestic heating in industrialized countries. While biomass continues to be used in open fireplaces, mainly for aesthetic reasons, where biomass is the main source of heating modern biomass conversion technologies are used, which provide high-quality energy services that are clean, efficient, and comparable in convenience with their fossil fuel alternatives. Estimating how much heat is provided via modern systems in industrialized countries is also difficult because the heat market is captive to the buildings, industrial processes, and locations being supplied. Government statistics tend only to record large systems, such as district heating networks and power plants.

Small appliances such as log burning stoves are only visible at point of sale, or if they use biomass that appears in retail statistics. Nevertheless, there is evidence of a growing market for modern boilers and stoves in the OECD. Within the USA, for example, it is estimated that approximately 800,000 households use wood as their primary heat source, whereas in the top nine European countries (Austria, Belgium, Denmark, Finland, France, Germany, Italy, Spain, and Sweden), the number of domestic stoves and boilers is estimated to exceed 1.3 million and accounts for the majority of solid biomass sold in Europe [25, 29].

In OECD countries, the volume of biomass for residential heat is expected to grow by 40–90% to reach 3.2–4.3 EJ in 2030 [3], as a result of a growing share of biomass in district heating systems and the growing market for modern boilers and stoves in buildings. Scandinavian countries – Sweden, Finland, and Denmark – are leaders in biomass residential heating, with large systems producing more than two thirds of the biomass heat. In Sweden, biomass is now the primary energy source for the district heat sector and in 2009 the share of energy production from biomass exceeded oil for the first time [25]. Sweden is the leader with biomass contributing close to 50% of its large-scale residential heat production, followed by Austria (24%), Finland (17%), Denmark (14%), and Norway (10%).

On average 5% of large-scale heat is provided by biomass in the USA and 7% in the IEA member countries [30].

Biomass is also used to provide process heat to a variety of industries, mainly agricultural and forestry product processing industries, where electricity is often produced in combination with heat. Other industries too use biomass fuels for their processes (e.g., the use of charcoal in the Brazilian steel industry). Industrial use of biomass was about 189 Mtoe in 2007 and is expected to grow to 292 Mtoe in 2030 according to the IEA's Reference Scenario [3].

Worldwide, the installed capacity for biomass-based power generation was about 46 GW in 2007 [3], with an estimated electricity production of some 259 TWh (roughly the annual total power consumption of Spain). This power production occurs mostly in:

- Co-firing plants in countries with coal power stations
- Combustion-based CHP plants linked to district heating systems (Nordic countries in Europe), and in large pulp and paper or food industries (e.g., Brazil, USA)
- Landfill gas units and MSW incineration and anaerobic digestion plants
- Dedicated biomass combustion plants fuelled with wood chips and agricultural residues (e.g., straw)

Biomass Use for Transport Fuels

Biofuels are a fast growing bioenergy sector. While Brazil has been producing bioethanol from sugarcane since the 1970s, it is only in the last decade that biofuel production has acquired global production significance. Biofuels, though, still represent only about 1.5% of total road transport fuel consumption and only account for some 2% of the final bioenergy mix (in energy terms) [2].

Bioethanol production has grown dramatically over the last decade. Nearly 80% of the global supply of biofuels is bioethanol from Brazil (from sugar-cane) and the USA (from corn/maize), where plants with capacities up to more than 500 million liters per year are found. Global biodiesel production has also grown significantly, with most production based in Europe, and companies in Germany and Austria having established themselves as leading technology providers. China and India also produce significant quantities of biofuels, mostly of bioethanol.

Bioethanol is used as a gasoline substitute and is generally blended with gasoline to different extents depending on fuel and vehicle specifications at levels between 5% and 10%. In Brazil, the ethanol blend level is higher (25%) and neat ethanol is also sold for use in vehicles. In the past, the use of neat ethanol required dedicated vehicles, but the successful and rapid introduction of flex-fuel vehicles now allows for switching between bioethanol and conventional gasoline, and any blend in between. In Europe and the USA, the introduction of flex-fuel vehicles has also led to the uptake of E85, a blend of 85% ethanol and 15% gasoline.

Biodiesel is used as a diesel substitute and is generally blended up to between 5% and 7% with diesel, mainly because of limitations imposed by fuel and vehicle specifications. Higher biodiesel blends are used in fleet vehicles (e.g., trucks and buses), generally in the form of B30, a blend of 30% biodiesel and 70% diesel. In Germany, 100% biodiesel has been used in vehicles, through a dedicated network of refueling stations.

Biomethane derived from biogas is used as a fuel, mainly for compressed natural gas (CNG) fleet vehicles. There were nine million vehicles in operation in 2007 compared with four million in 2004. Sweden, with a fleet of 15,000 CNG vehicles, has a share greater than 55% of biomethane in natural gas for transport, and Switzerland over 35%. Germany and Austria are both aiming for 20% by 2020 [31].

Global biofuels supply reached about 0.8 million barrels per day in 2008, with most of the use and growth in production in North America and Europe. Biofuels growth remains largely driven by energy security and climate change policies, with agricultural policy also playing an important role. The industry, however, is subject to the vagaries of the oil price and agricultural commodity prices, with dips in oil prices and rises in the prices of sugar, starch, and vegetable oil commodities cutting the profitability of biofuel production and placing financial strain on producers. The growth of the biofuels industry will also depend on its environmental and social sustainability.

The use of lignocellulosic feedstocks promises access to a greater resource and greater GHG reduction potential than current ethanol and biodiesel production from sugar, starch, and oil crops. But routes based on lignocellulosic material are in the early days of

commercialization. New biofuel technologies also allow biofuels to penetrate other transport fuel markets such as aviation fuel (e.g., production of jet fuel from Fischer Tropsch or hydrotreating routes).

Future Directions

Energy security and climate change policy are the main drivers for the expansion of bioenergy use. Agricultural policy has been – and continues to be – an important driver. Rising fossil fuel prices also mean that bioenergy is increasingly competitive in heat, electricity, and transport applications. However, bioenergy will compete for economic resources with other low-carbon and oil-substituting technologies in the different sectors.

The best use of biomass depends on how it can best contribute to overall energy system goals. There are likely to be trade-offs between the different attributes bioenergy may contribute to meeting these goals in the different sectors. For example, appreciating where bioenergy can have the greatest impact on GHG emissions reduction relies on both an understanding of the emissions savings which could result from different bioenergy routes and the importance of bioenergy in reducing emissions in a particular sector relative to other low-carbon options.

The potential for innovation in bioenergy remains large, and so is its potential to contribute effectively to the future energy system across heat, electricity, and transport applications.

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Biomethane from Anaerobic Processes

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Article Outline

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Glossary

Biomethane Biomethane is produced in technical processes from biogenic resources. It can be generated via the biochemical pathway (from biogas) and via the thermochemical pathway (Bio-SNG). Through upgrading processes, its composition, focusing mainly on the methane content, is adapted to natural gas quality.

Biogas upgradation Biogas upgradation is the process which adapts the biogas quality to natural gas quality after cleaning the biogas from trace gases (H₂S, NH₃, water vapor, and others). Within this process, mainly carbon dioxide is removed from the biogas.

Biogas Biogas is a gas that is produced as waste product during anaerobic microbiological breakdown of organic substances.

Landfill gas Landfill gas is a special type of biogas produced in landfills from the degradation of the organic constituents of wastes. It is characterized by many organic long chain trace gases.

Sewage sludge gas Sewage sludge gas is a special type of biogas that is produced at wastewater treatment plants during the anaerobic treatment of sewage sludge. It is characterized by the content of siloxanes.

Definition of the Subject and Its Importance

This entry focuses on the development, its reasons, and the perspectives of biomethane supply from biogas through anaerobic digestion. This option becomes more and more important due to the political requirements for reduction of greenhouse gases as well as for raised independency on fossil fuels coming from abroad. Thus, a detailed analysis of market development as well as technology development of this sector with about 10 years experiences is done to discuss the possibilities and the challenges of biomethane supply and its contribution to reach these targets.

Introduction

Biomethane can generally be produced following two pathways. The first and more established one is the upgradation of biogas from anaerobic digestion of wet biomass. The second one is the cleaning and upgradation of gas derived from thermochemical treatment (gasification) of solid dry biomass (e.g., wood). This is illustrated in Fig. 1.

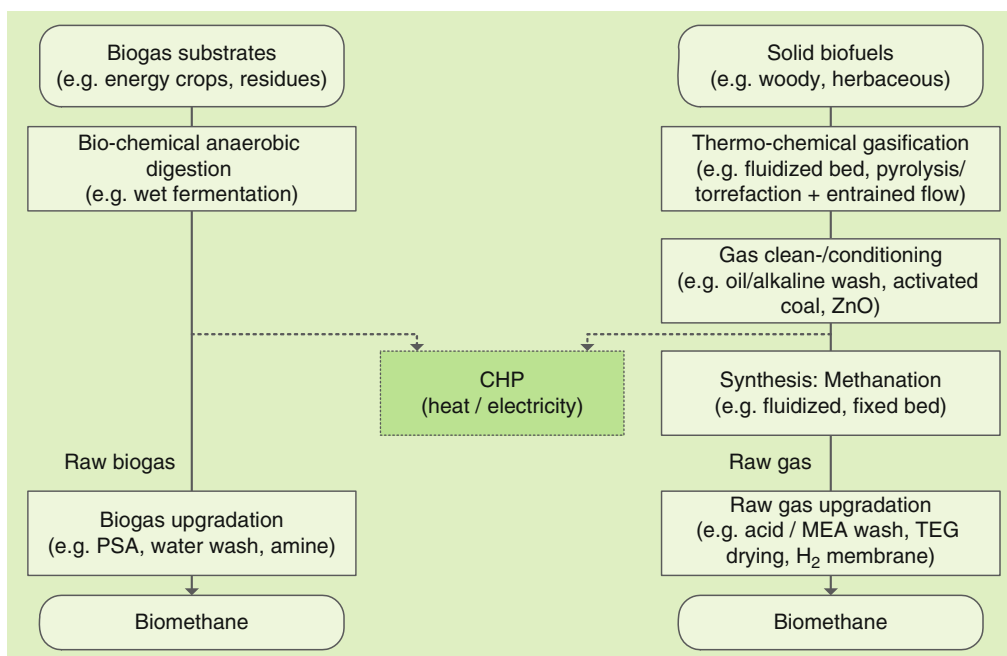
This entry will only focus on the anaerobic digestion pathway of biomethane supply having more than

10 years history in industrial scale application and a strong technological development during this time. The development depends on several factors – the main two are the reduction of greenhouse gas emissions from energy supply on the one hand and the supply of a decentralized available energy carrier independently from international markets on the other hand.

The main technological challenge of biomethane supply is the energy-efficient separation of almost pure methane from biogas containing a large share of carbon dioxide and shares of nitrogen, oxygen, hydrogen, hydrogen sulphide, ammonia, and other trace gases. Due to the market development today, a lot of technologies are available and under research.

The economic challenge of biomethane supply is the cost effectiveness in comparison with fossil and renewable fuels. In most cases, this is still not given today and governmental measures are in place in many countries to force the development of this technology.

Based on this background the following description will bring some light into the history of biomethane production including some examples of biomethane plants in the world. Furthermore the reasons for this development will be analyzed looking



Biomethane from Anaerobic Processes. Figure 1
Pathways of biomethane production

into the realized and necessary framework conditions for the technology. This will be followed by an overview on the technologies applied and under research with their development potentials. The explanations are continued with an economic outlook for this technology. Finally some conclusions are drawn on the future research demand and the overall perspectives of the technology.

History of Biomethane Production and Utilization

Biogas has been produced for decades in industrial scale for various reasons (e.g., as means to reduce and stabilize sewage sludge and other wastes, to stabilize landfills, to reduce eutrophication within the agricultural sector, and last but not least, in times of energy supply limitations for decentralized energy provision). Usually the produced biogas is used to cover the need for cooking energy, for heat, or for electricity at the production site. However, mismatch between the biogas production and the local heat demand normally results in flaring, which from a resource and energy efficiency perspective is devastating. The increased environmental concern and the possibility to take advantage of the energy that otherwise would be burnt off in a flare have resulted in new solutions such as biogas upgrading and grid injection.

The biogas upgrading development took off in the 1980s and early 1990s through demonstration and

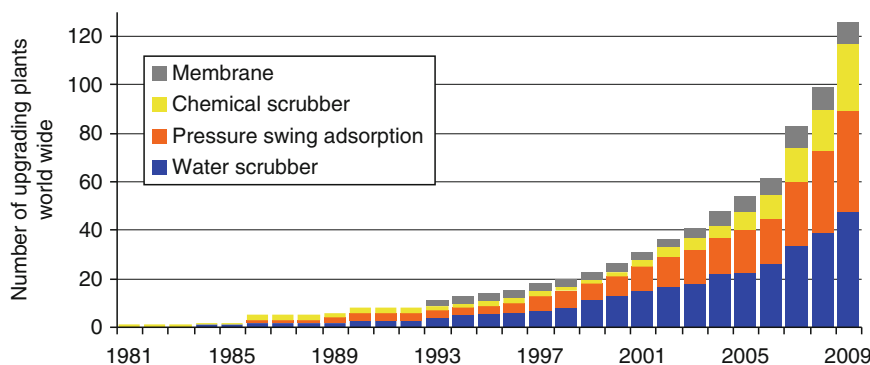
industrial scale plants in France, Sweden, Switzerland, The Netherlands, and the USA. While the focus in The Netherlands and the USA was on upgrading of landfill gas for grid injection, the focus in Sweden and Switzerland was on upgrading biogas to vehicle fuel.

Figure 2 illustrates the development of the number of upgrading plants worldwide, and Fig. 3 visualizes the installed capacity of upgrading plants. Both figures show the exponential growth of the sector. The capacities are with about 50% dominated by relatively few very large landfill upgrading plants, located preponderant in the USA. The worldwide distribution of the plants is illustrated in Fig. 4.

As examples of the variety of applications below are some of the early plants described.

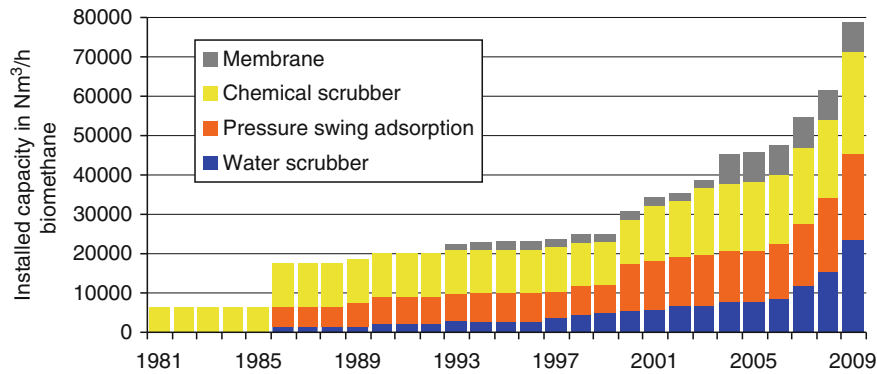
Tilburg, The Netherlands

The upgrading plant based on water scrubbing was built in 1986, when utilization of the gas from landfills began. The landfill facility was later complemented with a biogas plant where vegetable, fruit, and garden (VFG) waste are digested. The capacity of the upgrading plant is 2,000 m³/h of raw gas from the landfill and the VFG-digester. The upgraded biogas has a methane content of 88% which gives a heating value and a Wobbe index similar to the natural gas produced in Groningen/The Netherlands. The upgraded biogas is injected into the Tilburg City distribution network [1].



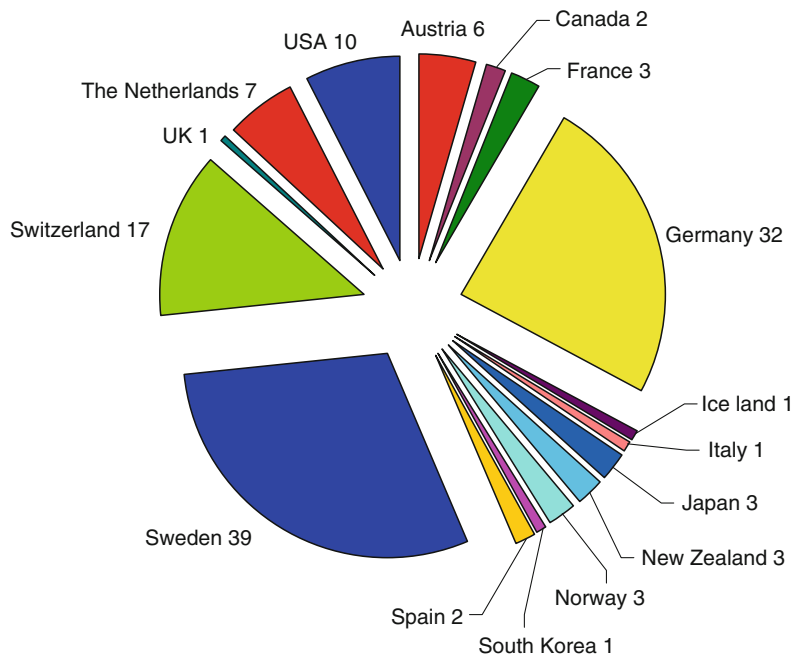
Biomethane from Anaerobic Processes. Figure 2

Development of biogas upgrading plants in operation worldwide



Biomethane from Anaerobic Processes. Figure 3

Development of the capacity of biogas upgrading plants in operation worldwide



Biomethane from Anaerobic Processes. Figure 4

Distribution of biogas upgrading plants in operation worldwide 2009

New York, USA

In 1982 an upgrading plant based on Selexol-washing technology has been installed at the Fresh Kills landfill on Staten Island, New York City. With a capacity of 13,000 m³/h raw gas, this was the first large-scale commercial application of landfill gas upgraded to pipeline quality and injected on a gas grid [2].

Lille, France

Up to 1990, 20% of the biogas produced by the wastewater treatment plant was burnt off and the rest used to supply heat and power to the treatment plant. With a production of 15,000 m³ per day, in average 3,000 m³ biogas (equivalent to 1,200 L of petrol) was flared every day.

To take advantage of the biogas surplus, the Urban Community of Lille decided by the end of 1990 to launch a project. The primary objectives of the project were to:

- Build a pilot site for the production of upgraded biogas
- Convert a conventional diesel bus into a biogas-powered bus

The biogas upgrading plant based on water scrubbing was commissioned in June 1995, and a distribution terminal was installed at the Marquette production site. The washing unit was designed to treat 100 m³/h raw gas. A new facility with a capacity of 1,200 m³ upgraded biogas was built in 2007. Compressed natural gas has been used to allow expansion of the gas bus fleet prior to the new facility was in place and to manage fluctuations in biogas production [3, 4].

Rümlang, Switzerland

The first upgrading plant in Switzerland was built in Rümlang by Kompogas in 1992. It was a pilot plant with a capacity of about 30 m³/h raw gas. The digester was fed with biowaste. Initially the upgrading system was based on water scrubbing. This has been changed in 1995 to a PSA. The upgraded biogas is used as vehicle fuel (A. Wellinger, 2009, Personal communication by e-mail 26-11-2009) [5].

Linköping, Sweden

In 1992, some of the biogas produced at the sewage treatment plant was upgraded in a small plant using the PSA technique. The capacity was 150 m³/h raw gas, and the plant supplied five city buses with fuel. A full-scale biogas plant was built at Åby, near Linköping, which started to operate in spring 1997. The upgrading, based on water scrubbing, has a capacity of 500 m³/h raw gas, and the upgraded biogas is used as vehicle fuel. A third plant, using the same upgrading technology, was built in 2002, with a capacity of 1,400 m³/h raw gas. Including the gas from the sewage treatment plant, approx. 65 million cubic meters of upgraded biogas is produced every year, which through a local gas grid supplies fuel to city buses, garbage trucks, and a number of filling stations. As Linköping has no natural gas pipeline, liquefied natural gas (LNG) is used as backup. A train

was converted from diesel to biogas in 2006. The train operates on the line between Linköping and Västervik and can run 600 km between each refueling [5].

Framework for Biomethane Production and Utilization

The development of application of the technology still depends on political support. In most cases the product biomethane is not economically competitive compared to natural gas. Thus the realization of biomethane projects requires financial support. Therefore in different countries different support schemes have been implemented. Therefore the situation in Sweden, Switzerland, Germany, and Luxemburg will be discussed due to the fact that the development is the most important worldwide (except Luxemburg as a special case).

Sweden

In Sweden most biomethane is used as green gaseous vehicle fuel. In fact the rapid development has led to a situation where the use of biomethane has surpassed natural gas in this sector. Due to the fact that the production cost of biomethane is relatively high compared to fossil fuels, biomethane is targeted for sectors where the benefits of a renewable high-quality fuel with low carbon dioxide footprint are valued. Thus the situation developed that large amounts of biomethane are used as fuel for cars, heavy vehicles, and buses. Additionally the largest grid operator is really interested in biomethane production and supply so that there were almost no reservations on biomethane.

The Swedish government supports through various subsidy schemes the investment into biomethane plants to raise the interests in the technology. This support system in combination with the very high strategic aims for greenhouse gas reduction in Sweden has led to a good development of the biomethane supply.

Germany

In Germany biomethane is used for different applications. Due to the fact that the German gas industry has published a self-commitment to supply from 2010 10% of the gas which is sold as fuel for vehicles, some biomethane is used on this pathway. The largest share of the gas is for sure used as fuel for combined heat and

power plants due to interesting feed-in-tariffs for electricity from biomass based on the so-called Renewable Energy Entry Act (German feed-in law). There it is stated that new plants for electricity production from biogas receive between 0.09 and about 0.2 €/kWh electricity fed into the electricity grid guaranteed for the next 20 years. These tariffs are no subsidies; they are defrayed by all German electricity consumers according to their electricity demand.

An increasing amount of biogas is also sold to private households, which can buy biomethane at market prices.

An additional support for biomethane use is the so-called Gas Entry Act. In this act, conditions for gas grid connection and a tariff for reduction of the grid use costs for the grid operator due to local gas feed-in ($0.006 \text{ €/kWh}_{\text{gas}}$) are defined. Additionally, regulations for the priority feed-in of biomass-based gases in comparison with fossil gases are given.

Switzerland

In Switzerland the associations of gas industry and biogas suppliers agreed on a voluntary system of feed-in-tariffs where specific remunerations for the gas amount per kilowatt hour are defined. On this basis the gas production is financed. The biomethane is prevailing used as vehicle fuel.

Luxembourg

In Luxembourg a guideline for direct feed-in-tariffs for biomethane into the natural gas grid in combination with clear rules for gas grid access will be implemented soon. Totally independent on the final use of the gas, these tariffs shall be economically sufficient for biomethane production processes. Tariffs will cover different financial efforts for biomethane production from different feedstock (e.g., sewage sludge, organic wastes, energy crops) as well as the economy of scale.

Conclusions

The first and most important framework condition is the opening of the gas grids and/or the possibilities for biomethane trading to force the development of biomethane production and use. Evaluating the effectiveness of the very different incentive models for

biomethane production especially systems which enable guaranteed refinancing of the investments over long periods seem to be most promising. An example is the system under establishment in Luxembourg [6]. From the administrative point of view, systems on the basis of voluntary agreements of the industry are probably the fastest way to introduce some incentives. Finally the level of inducement of plant construction and operation depends clearly on the absolute height of financial incentives. In the case of high incentives (subsidies or feed-in-tariffs), it has to be taken into account that the market could overreact so that after a first boom of plant construction, lots of companies could get into troubles with a very fast growth what could be seen in Germany in 2008 and 2009. Thus the incentives should be chosen very carefully to get a sustainable market development for biomethane production and use.

Technologies for Biomethane Production

Generally it has to be differentiated between two main steps of biomethane production using biochemical processes. That is biogas production and biogas upgradation.

Biogas Production

Biogas production has to be seen as state of the art. A huge variety of different technologies are available on the market depending on the feedstock characteristic. An economically efficient biomethane supply requires a minimum plant size. This has some influence on the substrates to be used for biochemical biogas generation. Based on analysis done for German conditions and considering the feed-in of biomethane into the gas grid, an economic biomethane supply requires a plant capacity of at least 200 m_N^3 biomethane. Experiences show that this capacity requires very large amounts of municipal and/or industrial organic wastes (about 30,000 t/a and more) or energy crops (about 15,000 t/a and more). Also sewage sludge from municipal wastewater treatment plants of large towns or huge landfills can be the source for the biogas. Excrements from animal breeding play due to the low energy content no important role for biomethane supply.

Biomethane from Anaerobic Processes. Table 1 Composition of biogas (from residues, waste, and energy crops digestion) wastewater treatment plant gas (from sewage sludge digestion) and natural gas

Component	Biogas	WWTP gas	Natural gas
Methane	50–70%	60–70%	93–98%
Carbon dioxide	25–40%	30–40%	1%
Nitrogen	<3%	4%	1%
Oxygen	<2%	1%	–
Hydrogen	Traces	Traces	–
H ₂ S	Up to 10,000 ppm	Up to 1,000 ppm	–
NH ₃	Traces	Traces	–
Ethane	–	–	<3%
Propane	–	–	<2%
Siloxanes	Traces	<6 mg/m ³	–

The most important obstacle of biogas utilization as a substitute for natural gas is the content of different compounds (e.g., CO₂, H₂S, NH₃). Table 1 shows the average composition. Biogas has due to its different composition to be differentiated into biogas from residues, waste, and energy crops and biogas from wastewater treatment plants where sewage sludge is digested.

Biogas Upgradation to Biomethane

The market share of the different technologies can be taken from Figs. 2 and 3. Upgrading technologies for biogas result mainly from technological applications from the natural gas sector where partly comparable upgrading tasks have to be solved, but at a by far larger scale. Until today, some technologies show long time experiences and others are relatively new.

Generally it has to be stated that all upgrading plants pledge to reach a biomethane quality of more than 96% methane content and a methane loss less than 3%. Additionally a very high availability for all technologies is promised. This has been confirmed in practice with an availability of about 95% at most plants [7]. Practical measurements have shown different results, but more or less independent of the used technology. Especially it seems to be necessary to care about the methane losses which are reported with at maximum up to 10% (typical range 0.1–3%), because

they influence environmental and economic parameters of such plants very strongly.

For all the described technologies, current research activities are reported with some focus on membrane technologies due to essential development successes at membrane processing. Technologies under research are the so-called process internal methane enrichment (or in situ methane enrichment) using the absorption of carbon dioxide in the liquid phase of fermentation and external reduction of the carbon dioxide concentration from this phase as well as the so-called ecological lung using the enzymatic dissolution of carbon dioxide with the enzyme carboanhydrase in a comparable process as in the lung [8].

Water Scrubbing One of the mainly used technologies for biogas upgrading is the water scrubbing process which shows a very long history of experiences.

This process is based on sorption of carbon dioxide in water at high pressures (about 10 bar) and desorption of carbon dioxide at lower pressures in another vessel to separate carbon dioxide and methane. At the same time, most trace gases (e.g., H₂S) are separated during this process. As water source circulated, fresh water or cleaned wastewater without circulation can be used. Advantages of wastewater use are compensated by biofouling in the scrubbers due to the relatively high organics content.

Due to the long research and development period, the technology has reached a very high level of development and is proven in practice. Thus, it has to be expected that the technology has to compete with other technologies in economic questions but is seen as technological state of the art.

Pressure Swing Adsorption The pressure swing adsorption technology is based on high-pressure adsorption of carbon dioxide at molecular sieves or activated charcoal in at least two steps. Other trace gases have to be separated, e.g., in filter systems before carbon dioxide adsorption. Adsorption materials have long operation durations but have to be exchanged from time to time.

This technology shows long time experiences and is well established and competes as solid and reliable technology in the market.

Chemical Scrubbing Chemical scrubbing is possible with a number of substances (e.g., Selexol, MEA, DEA), which are capable to absorb carbon dioxide at ambient or low pressures mostly combined with heat demand for desorption. Available information about efficiencies of the processes is very different, but a lot of experiences exist and research is going on. The advantage of chemical scrubbing is that used substances are selective for carbon dioxide (and sometimes for H_2S too, most times H_2S -separation is done before upgrading), and thus no methane will be absorbed resulting in high methane concentrations in the purified gas and low methane emissions. Adsorption processes under pressure seem to be of comparable behavior as water scrubbing processes. Ambient pressure systems promise less electrical energy demand for the continuous process and could be of high interest for applications where only low pressure is required after upgrading and heat is available [7].

For the time being, some chemical scrubbing technologies are reliable and well established and others are under development.

Membrane Technologies Due to the different molecule sizes of methane and carbon dioxide, it is generally possible to separate both gases through membranes. The smaller methane molecules can pass through

a membrane, and a gas with very high methane content and a gas with very high carbon dioxide content can be produced. Technologies were developed for dry separation (transport through the membrane is forced by very high pressure) and for wet separation (transport is forced by a very low concentration of methane in a fluid which methane is absorbed in). Both technologies are known from long running plants and improved technologies from pilot plants. Efficiencies regarding methane losses and energy demand of improved technologies are subject of ongoing evaluation. The most important challenge is to reach comparable high methane concentrations and low methane losses as reached by the established technologies.

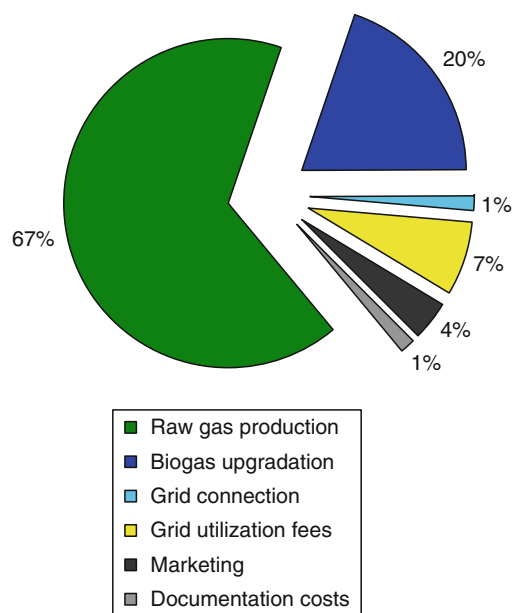
Cryogenic Upgrading Additionally it is possible to use the differences in dew and condensation points of methane and carbon dioxide. Therefore it has been shown in small scale as well in large scale that both gas components can be separated by cooling down of biogas to less than $-45^\circ C$ at about 80 bar pressure.

Economics of Biomethane Production and Utilization

Economics of biomethane supply will predominantly affect its future utilization. At production costs between 0.05 and 0.08 €/kWh_{gas}, biomethane is not really competitive with natural gas at import costs of 0.02–0.03 €/kWh_{gas}.

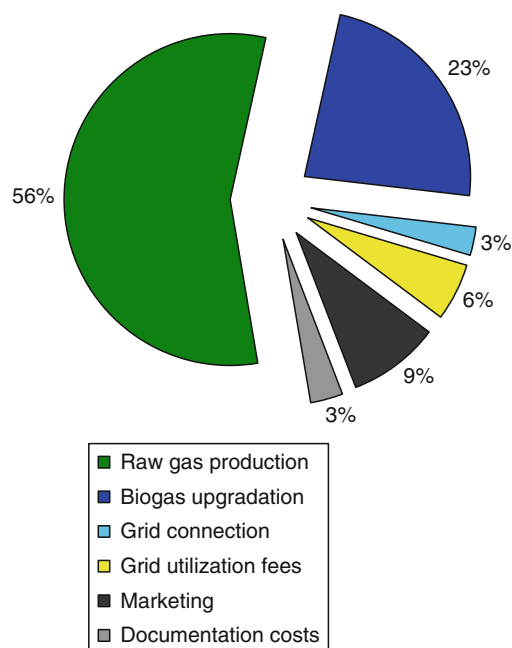
Looking in the different cost positions of biomethane at a German example of a plant based on energy crops digestion (which show the highest potential for the growth of this sector in the future), the costs result from raw biogas production including the costs for substrate supply (about 50% of this position), costs for biogas upgradation to biomethane, and the costs for gas grid injection, transportation as well as feed-out (Fig. 5).

Looking into the future, it is expected that energy prices will still increase. So it has to be assumed that biomethane prices and natural gas prices will cross any time. But for sure this will not happen before the natural gas prices have doubled. Although there are many activities for improvements of raw biogas



Biomethane from Anaerobic Processes. Figure 5

Distribution of biomethane supply costs at the point of feed-out from the gas grid under German conditions for a plant at 1,500 Nm³/h biomethane supply from energy crops digestion



Biomethane from Anaerobic Processes. Figure 6

Distribution of biomethane supply costs at the point of feed-out from the gas grid under German conditions for a plant at 500 Nm³/h biomethane supply from energy crops digestion

production and biogas upgradation, in the short term, improvements can be expected allowing achieving up to 20% cost efficiency. But this will partly be compensated by the general price increase.

Looking into the cost distribution of a smaller plant (Fig. 6), it is visible that the total share of raw biogas production and upgradation decreases. Thus, cost efficiency in these sectors will have smaller effects.

Contradictory the share of the costs for gas grid access and transportation grow due to the fact that absolute costs for the gas grid access are not dependent on the capacity of the plants.

As a result, it must be stated that cost reduction potentials at gas grid distribution of biomethane should be more investigated and reduced for further growth of the biomethane industry. It would additionally be necessary to achieve significant cost reductions to optimize the biomethane production. This could be

realized with reductions of requirements for biomethane feed-in plants and sharing the costs of feed-in with the gas grid operators.

Future Directions

It is expected that the trend of the last decades will be rapidly continued in the future regarding plant numbers and capacities worldwide with a special focal point in Europe. Due to effects of the economy of scale and the limited availability of cost-effective small-scale technologies for gas upgradation and gas feed-in the size of plants for gas grid injection will still be relatively large in the range of 200 m³ biomethane and more.

Depending on the crude oil and natural gas price development, the speed of the growth will vary. But international targets for greenhouse gas reductions and financial measures to support the use of renewable

energies will force a wide use of this technology. Full economic competitiveness regarding profits from natural gas trading and utilization within the next few years is not to be expected. But the current development in some countries shows that economic models for biomethane production and use are applicable.

Moreover, biomethane is the only renewable energy carrier which can – due to its high quality – substitute gaseous fuels without technical adaptations of the consuming applications. And it has the full flexibility of utilization for heat, electricity, and fuel supply that can be distributed and traded on a global market.

Research activities for technology improvement are still going on so that the challenges of decrease of environmental negative effects (energy consumption, greenhouse gas emissions) of increased gas quality as well as decreased costs will be solved in the years to come.

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Bioremediation and Mitigation

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Article Outline

Glossary
 Definition of the Subject
 Introduction
 Bioremediation Technologies Available for Sustainable Mitigation
 Mitigation Case Studies with Petroleum and Related Hydrocarbons
 Future Directions
 Conclusions
 Bibliography

Glossary

Bioremediation Bioremediation can be defined as a process using a microbial community and/or the related enzymes to return the natural environment altered by contamination to its original condition. Bioremediation can also be considered an industry that uses these techniques to solve real-world problems. Bioremediation is an applied field of science that combines advanced biotechnology and engineering approaches with basic microbiology to solve complicated challenges in soil water and groundwater contamination [1].

Biodegradation/biomineralization The process in the carbon cycle of using a microbe/microbial community (bacteria, fungi, yeasts, actinomycetes) or plants to convert complex carbon-based chemicals (organic matter) to simpler structures and biomass. The complete conversion of said chemical to its mineral form, namely, biomass, water, and CO₂ is called biomineralization. The process is described as aerobic if oxygen is required by the biological community and anaerobic if it is not required or present [1].

Mitigation The effort to eliminate or reduce loss and/or impact to habitat, life, property, or natural

resources. Hazard mitigation means any action taken to reduce or eliminate the long-term risk to human life and property from natural hazards (Stafford Act 44: CFR 206: 401) [1, 2].

Polycyclic aromatic hydrocarbons (PAHs) Lipophilic, fused, aromatic rings typically found in compounds of oil, coal, tar deposits or residuals from burning any fossil fuel. Also known as polynuclear aromatic hydrocarbons, several are considered to be potential human carcinogens by USEPA. Benzo(a)pyrene is considered a benchmark regulatory toxicant for bioremediation of most hydrocarbon-contaminated sites [1].

Sustainable remediation Practices or multitasked approaches for restoring a site to its native state with a frugal use of available resources so as to benefit human health and the environment [1].

Definition of the Subject

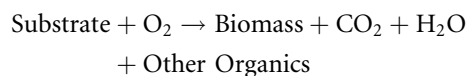
The high costs involved with conventional remedial techniques and frequently, the liability associated with the use of such techniques, has encouraged industry to search for innovative remediation technologies. The use of innovative technologies that provide a cost-effective and permanent treatment method is gaining the attention of regulatory agencies, the public, and, most importantly, the industries responsible for cleanup. In order to address these needs, research organizations and engineering firms are testing various innovative technologies in the laboratories and in the field. One such technology, bioremediation, is currently gaining more and more acceptance and has proven to be a cost-effective mitigation strategy [3].

The US Environmental Protection Agency has been at the forefront in promoting bioremediation as an innovative solution for addressing risk-based regulatory challenges for the cleanup of contaminated soils, sediments, groundwater, and industrial effluent. The establishment of specific criteria for acceptable levels of exposure in soils and sediments, groundwater, and/or discharge into rivers and streams has hastened the recognition of applying specific microbial cultures and/or communities to mitigate in a sustainable effort [4–6].

Introduction

The practice of using microorganisms to clean up contamination can be traced back as early as 600 BC. It was

common practice to treat municipal wastewater by building intricate sewage systems that would transport wastewater to collection vats and lagoons where microbes would aid in the biodegradation of organic wastes. Today, this same principal can be used to clean up modern pollution problems like chemical spills and tank leaks [6]. This process is the utilization of a consortium of microbes to degrade organic pollutants. Through bioremediation, toxic pollutants can be broken down into nontoxic byproducts such as CO₂ and water. Aerobic heterotrophs have enzymatic systems capable of oxidizing suitable substrates by transfer of electrons to molecular oxygen. To put it in simple terms, this process is performed through the following reaction:



Typically, in an aerobic or oxygen-requiring bioremediation, the contaminant degrading potential of these microorganisms is enhanced through the addition of essential reactants (inorganic and organic nutrients, water, and oxygen) [6, 7]. Biodegradation of complex organic pollutants may require a series of concerted metabolic events involving several species of bacteria or coupled interactions with bacteria and fungi [8]. Slader and Godwin [9] described the basic reactions in microbial metabolism as:

- Enzymatic catalyzed degradation of aliphatic hydrocarbons where the end products of beta-oxidation are organic alcohols and acids
- Enzymatic catalyzed hydrolysis, acidification, and ring cleavage of the benzene ring
- Production of homeostatic enzymes which regulate the well-being of the organisms by coordinated responses that automatically compensate for environmental changes
- Com metabolism, which involves use of readily degradable hydrocarbons in combination with fortuitous transformation of a desired pollutant

Microbial Parameters for Successful Mitigation

Bioremediation is clearly an interdisciplinary field involving expertise from engineering, geology, chemistry, and ecology [10]. Numerous approaches to soil and

sediment remediation have been developed and implemented on an international basis. A common goal in all of the processes is to create the necessary environment for the growth of an optimal microbial community which can, in an effective manner, biodegrade contaminants of concern [11, 12].

The rate and extent of contaminant biodegradation using any natural process can be affected by numerous factors including, the actual structure of the contaminants of concern, its solubility and water bioavailability, co-oxidation/cold metabolism potential, relative toxicity, and its interaction with other properties in soil and sediment. Oxygen plays a dominant role in the selection of appropriate microbial communities for biodegradation to proceed. Water content in either bound water or groundwater is equally important in that water serves not only as a universal solvent but also has as a facilitator of movement of important nutrients and buffers for microbial biodegradation process initiation. Other limiting factors which affect the efficacious use of microorganisms to remediate contaminated soils or sediments include but are not limited to temperature, pH, organic and inorganic soil content, and the presence of metals such as arsenic, lead, and mercury [13–15].

Contaminated sites present the problem of attempting to biodegrade a diverse mixture of contaminants. A typical example is oil, the mixture of chemicals with different molecular weights, latent heat of vaporization, and relative water solubility. This necessitates the requirement of careful characterization of all constituents within the mixture. Therefore, remediation approaches are often dictated by the relative quantity of the most recalcitrant chemical in the mixture [14].

Bioremediation as a mitigation tool has the additional problem of project specificity, that is, requiring a case-by-case evaluation of the suitable bioremediation approach as dictated by the challenges of each specific site. Thus no one all-encompassing bioremediation tool or remedy will work for all contaminated sites. The remediation services market represents less than 5% of the \$250 billion annual environmental industry market and is limited in its further expansion by the requirement of designing site-specific solutions using an adapted microbial community. However, the significant savings to both the public and private sector

in using a microbiological approach to cleanup sites continues to be the major driver for looking at mature and evolving bioremediation technologies as a solution to mitigation challenges.

Candidate Contaminants for Bioremediation

Candidate contaminants for bioremediation processes have been successfully used to remediate petroleum hydrocarbons such as gasoline, diesel fuel, crude oil and creosote; pesticides and their derivatives such as phenoxyacetate herbicides, carbamates, and organophosphates; chlorinated solvents such as methylene chloride, trichloroethylene, and vinyl chloride; and halogenated aromatic hydrocarbons such as pentachlorophenol, chlorinated benzenes, and even some polychlorinated biphenyls (PCBs) [16–18].

Because of the nature of bioremediation, it is most applicable toward detoxification of organic wastes, most of which are at least theoretically biodegradable [19–21]. Among the most recalcitrant organic contaminants are the organohalogens, which, because of their rarity in nature, are persistent, as few biological systems have evolved to degrade them [19]. In contrast, petroleum hydrocarbons (PHCs) are relatively easily degraded [20, 21]. Historically PHCs entered the environment only via sporadic seepage and erosion, which allowed for the development of some natural microbial biodegradative pathways. In recent history, however, man's increasing reliance on fossil fuels has resulted in dramatic increases in petroleum hydrocarbon pollution [21]. Currently the combined chronic marine and terrestrial discharges of PHCs account for greater than 90% of anthropogenic environmental pollution [21].

Advantages of Bioremediation

Microbiological processes can be used as the keystone technology to develop cost-effective remediation systems for hazardous/nonhazardous waste sites. Bioremediation can be much cheaper than other technologies, approximately one third to one half the cost of transport and incineration of similar volumes of waste. In addition, byproducts that require landfilling such as incineration ash are not produced [23]. As the technology of bioremediation methods advances, the market for bioremediation products has also increased.

Microbial pollution products to be used in remediation projects, including dried or liquid microbial inocula with or without nutrient additives, have annual sales of \$7–10 million and the potential market may reach \$200 million [13].

Additionally, in situ bioremediation reduces the risk of exposure during cleanups by avoiding the need for excavation [22]. Bioremediation shows promise for further reducing the low levels of contaminants left after excavation of high level contaminants [22]. Bioremediation is a natural process that has the potential of degrading toxics and other wastes to harmless products – carbon dioxide, water, and fatty acids – when the process is completed [17, 22]. An in situ bioremediation system can serve as a permanent in-place management system. The installation of an in situ bioremediation system can be accomplished with minimal site/business disruption and public exposure [23]. Bioremediation is currently applied to a wide range of site conditions and contaminants, from oil-contaminated beaches in Alaska to PCB-contaminated soils in Florida [24]. It is at the forefront of a larger group of innovative remediation technologies.

Bioremediation depends on the natural selection of organisms that have the capacity to metabolize xenobiotic chemicals. Many of these organisms occur naturally in contaminated areas, and the growth of these populations can be enhanced by the addition of nutrients and oxygen. Degradation of contaminants that resemble natural compounds is more rapid than with complex organic molecules such as dieldrin [6, 25].

Disadvantages of Bioremediation

Contaminated sites may differ greatly in terms of both microbiological and physiochemical parameters. Previous biodegradation at long-standing sites may result in increased proportions of components of greater recalcitrance. Greater assessment details are required for proposed biological treatment prior to cleanup to determine the impact of the chosen methodology upon the microbial population [26].

Actual experience with the bioremediation technology is limited when compared to conventional remediation technologies such as incineration, and competing technologies can usually be completed in less time. The present body of knowledge on

bioremediation is widely dispersed and often inaccessible, since much of it is considered proprietary. Bioremediation is not effective in the destruction of metals [27–29].

Soils and sediments are extremely complex mixtures with many microenvironments and vast arrays of living organisms. This complexity and other factors enhance the efficient chemical or physical attack on a molecule, leading to its degradation. Consequently, it is often difficult to distinguish between the microbial, chemical, and physical factors that contribute to the removal or transformation of a molecule [17, 30, 31].

Environmental limitations to biodegradation include: (1) toxic levels of waste, (2) lack of oxygen, (3) unfavorable pH, (4) lack of nutrients, (5) lack of moisture, and (6) unfavorable temperatures [17, 32]. These limitations can be circumvented by environmental manipulation either ex situ as in a bioreactor or in situ using appropriate amendment strategies. Parameters such as waste loading, pH, nutrients, and size of organism populations can be controlled and lead to maximum degradation rates. This type of manipulation is most effective for liquid wastes. Groundwater containing the organochlorine, toxaphene, and the organophosphates dioxathion and methyl parathion have been biologically treated ex situ using two reactors containing adapted *Acinetobacter* spp. immobilized on a support material. The bioreactors were operated over a 90-day period at a flow rate of 80 gallons per day. The microorganisms degraded 60% and 35% of the chlorinated and phosphate wastes, respectively [33].

The physicochemical bioavailability of any polluting chemical mixture in soils/sediments can be affected by its sorption equilibrium, irreversible sorption, and degree of incorporation into humic material. Mass transfer limitations can include oxygen diffusion and solubility, the relative rate of diffusion of nutrients, and the solubility/miscibility with water. Oxidation/reduction potential and the availability of electronic receptors as dictated by the presence or absence of oxygen plays a role in microbial population speciation and density [4]. Finally, not only is the chemical structure of the contaminants of concern and its relative solubility important in the overall efficiency of the mitigation process, the net concentration of the chemical itself plays an important role [5]. The induction of

suitable enzymes for effective bioremediation and subsequent growth and enrichment of a capable microbial community is often dictated by the limits of detection of each chemical in the mixture at the cellular level [17].

Single Species Versus Community Approaches

Many studies evaluating the microbial degradation of chemicals and soil, sediment and groundwater usually follow a reductive approach into a single microbial strain characterized on a chemical constituent basis [34]. Each organism is identified by either traditional selective culture approaches or amplified rDNA restriction (a simple method of identifying microbial community structure by characterizing DNA sequences indicative of temporal changes in the indigenous microbial population).

Simple screening studies of site soils/water for important microbes at the species level, which may be effective, and degrading chemicals of concern are evaluated in shaker flask studies or microcosm studies (a variable specific simulation of the complex field remediation challenge). Data sets generated can give an indication as to the appropriate degradation pathway necessary for site remediation. The screening data sets at the single species level also sets the stage for optimizing site conditions to insure a multiple species or community approach will be viable [34].

The issue of releasing genetically engineered microorganisms (GEM) whose genetic material has been altered into an ecosystem has become a controversial one. Critics contend that an ecosystem imbalance caused by a genetically adjusted organism could lead to disastrous consequences. The genome of the microbial population would be altered and the results of the genetic manipulation, when known, would be too late and could not be changed [34]. There are questions of economics, production, quality control, application, host specificity, and safety. It may not be economically feasible to develop a stable population, ensure integrity by quality control and apply microbial pesticides on a large scale. These organisms should only affect a target population, but in many cases it is difficult to predict whether a microbial pesticide could affect non-target organisms [35]. Engineered organisms can lose or alter the gene(s) that allow them to degrade

a specific toxicant after several generations, rendering them useless in bioremediation [36]. The advantages of isolating an organism which has adapted naturally to the degradation of waste products are many, and eliminates the issues with using GEM.

Economics

There are several remedial technologies that may be considered when determining corrective action for any site. The technologies discussed are nonbiological approaches like soil venting (including vacuum extraction), soil flushing, hydraulic barriers, and excavation. The first three methods are considered in situ treatment methods, remediation of those soils in their original location. The fourth method, excavation, is normally combined with off-site disposal, incineration, soil washing, or enhanced volatilization. A comparison of costs associated with each of these technologies is shown in Table 1. When considering each of these technologies, costs as well as site-specific variables must be considered in determining the most effective method [37].

In situ and Ex situ Bioremediation Approaches

Bioremediation methods and/or technologies are broadly classified as either ex situ or in situ processes.

Bioremediation and Mitigation. Table 1 An economic comparison of remediation approaches

Remedial methods	Treatment costs ^a
Soil venting (including vacuum extraction)	\$130–180/yd ³
Land farming	\$60–123/yd ³
Soil flushing	\$200/yd ³
Hydraulic barriers	\$67–88/ft ²
Off-site disposal (including excavation and backfill)	\$155–275/yd ³
Incineration (including excavation and backfill)	\$235–675/yd ³
Soil washing (including excavation and backfill)	\$185–235/yd ³
Enhanced volatilization (including excavation and backfill)	\$300/yd ³

^aUS Dollars, 2010

Ex situ methods require the physical removal of contaminated material prior to the initiation of the treatment process. In situ approaches involve treatment of contaminated soil sediment and or groundwater “in place.” Since bioremediation is a mitigation tool used for treating contamination in heterogeneous environments with complex phase separation of many materials by relative water solubility, the ability to successfully mitigate without physical removal and transportation to another location with its inherent risks of recontamination is desirable. The treatment of the Alaskan shoreline of Prince William Sound from the Exxon Valdez oil spill is an example of the successful use of an in situ approach to bioremediation [39].

Bioremediation Technologies Available for Sustainable Mitigation

The following technologies have been effectively used for sustainable remediation and are recognized as approved technologies by USEPA and other national environmental agencies [37, 40, 41]:

- *Bioaugmentation or Enhanced Bioremediation*: a process of amending contaminated media with microorganisms (bioaugmentation) and or nutrients (biostimulation) to degrade/immobilize/accumulate contaminants of concern.
- *Natural Attenuation (NA) or Monitored Natural Attenuation (MNA)*: the use of natural attenuation processes, that is, biodegradation/biomineralization, to achieve site-specific remediation objectives within a time frame that is reasonable compared to those offered by more active methods. As a natural biological and chemical process, NA is considered a natural process in achieving the goal of reducing mass, toxicity, mobility, concentration, and net total volume of a contaminant or mixture of contaminants in soil or groundwater. Risk assessment guidelines are used to ascertain whether remediation objectives are realized.
- *Bioventing*: an in situ remediation technology that uses indigenous microorganisms to biodegrade organic constituents absorbed to soils in unsaturated zones. Soils in the capillary fringe and the saturated zone are not affected. In bioventing, the activity of the indigenous bacteria is enhanced by inducing air or oxygen flow into the unsaturated zone using extraction or injection wells and, if necessary, by adding nutrients.
- *Bioplugs and Bioconduits*: an in situ technology that uses preselected acclimated microorganisms permanently immobilized or attached to a porous matrix and inserted into soils/sediments as a seeding device for both saturated and unsaturated zones. Microbial activity is maintained by using contaminated site water or ground water as a carbon nutrient source.
- *Biopiles*: also known as biocells, biomounds, or bioheaps; are excavated soils/sediments amended with minerals, nutrients, and water so as to reduce concentrations of contaminants in with indigenous microflora.
- *Composting or Compost Piles*: a variation of biopiles in which organic contaminants (e.g., PAHs) are mixed with lignocellulosic materials so as to biodegrade and/or cometabolize the recalcitrant constituents as the acclimated microbial population converts simpler carbon (under aerobic and anaerobic conditions) to innocuous, stabilized residuals.
- *Landfarming*: one of the oldest full-scale bioremediation technologies dating back to the treatment of process residuals from oil refinery operations. Also known as land treatment or land application, it is an above-ground remediation technology in which contaminated soils, sediments, or sludges are tilled or “turned” using standard farm cultivation equipment and allowed to slowly biodegrade as the acclimated soil microbial populations reduce the concentration of contaminants over time. It is one of the more widely used processes for handling large volumes of contaminated soils/sludges but requires significant acreage for repeated dispersal in layers or “lifts” over time.
- *Bioslurry or Liquid Solids Contact (LSC) Reactors*: an aqueous slurry in either a tank or lined impoundment that is created by combining soil, sediment, or sludge with water and other additives. The slurry is mixed to keep solids suspended (at a ratio of 30–40% volume:volume in water) and microorganisms in contact with the soil contaminants. Upon completion of the process, the slurry is dewatered and the treated soil is distributed in a land farm for

further biodegradation and dewatering by evaporation.

- *Online Bioreactor Systems*: the treatment of contaminants in extracted ground water that are put into contact with microorganisms in attached biological contractors (e.g., rotating and trickling filters) or suspended growth biological reactors (e.g., activated sludge). The technology is sometimes referred to as “pump & treat” technology.
- *Phytoremediation*: the use of plants to remediate contaminated soil and groundwater. However, different plant systems have individual mechanisms by which they extract (or accumulate), stabilize, volatilize, and/or degrade the contaminants, which is discussed in detail below.
- *Constructed Wetlands or “Rock and Reed” Systems*: treatment systems that have been designed and constructed to utilize the natural processes involving rock, clays, and specific wetland vegetation with a large root rhizosphere so as to allow surface and subsurface attached, associated microbial population to assist in treating contaminated water.

Mitigation Case Studies with Petroleum and Related Hydrocarbons

Over the past several decades, humans have grown more and more reliant on fossil fuels. Many of the comforts that humans enjoy today are possible largely because of fossil fuels such as petroleum. This intensification in use has resulted not only in an increased dependence but an increase in petroleum-related pollution. It has been estimated that petroleum contamination into the environment is between 1.7 and 8.8 million metric tons annually, most from anthropogenic sources. The manufacturing, transportation, and distribution of petroleum-based products over the past century have led to an increase in the amount of petroleum hydrocarbon pollution. Leaks, spills, and other accidents have all contributed to the contamination of air, soils, and water bodies by petroleum. Pollution can come from oil tankers, pipelines, and above and below ground storage tanks [42].

The pollution poses risk to human health and the environment. Although considered a nonhazardous waste by law, petroleum is a regulated contaminant. Most of the danger associated with petroleum-contaminated

sites comes from lighter weight hydrocarbons such as BTEX (benzene, toluene, ethylbenzene, and xylenes) and from fire hazards caused by vapors. Petroleum or any other type of contamination also makes initiating new construction projects on contaminated sites more challenging. It can impede the construction process as cleanup must occur and environmental standards must be met before construction begins. Petroleum hydrocarbons, as pollutants, fall into an intermediate category in their degradation between highly biodegradable, biogenic, and highly recalcitrant xenobiotics. Fortunately, these hydrocarbons can usually be readily degraded by microorganisms present in the environment. This fact makes treatment of petroleum hydrocarbon-contaminated areas more feasible [33].

Many treatment methods, however, are expensive and not complete in cleaning up petroleum waste. Partial contamination may still reside in soil or groundwater. Consequently, new techniques, such as bioremediation, are required to clean up petroleum wastes more completely and at a cheaper cost.

Categories of Petroleum Hydrocarbons

Petroleum hydrocarbons (PHCs) can be divided into four structural categories: saturated or aliphatic, aromatic, asphaltic or polar, and resins [18, 20, 24]. Aliphatic and saturated constituents can either be cyclic or acyclic compounds with or without carbon-carbon multiple bonds. Examples include pentene, pentane, and cyclohexane. Aromatic components are unsaturated cyclic compounds such as benzene and its derivatives [44]. Asphaltenes are highly condensed partially oxygenated compounds that occur in crude petroleum and are particularly resistant to biodegradation. Resins include oxygen, nitrogen, and sulfur-containing compounds that are for the most part recalcitrant [18, 23, 24]. Various characteristics of PHCs affect their inherent biodegradability; the chemical structure of individual components of petroleum products is most important, but physical state, toxicity, influence of other compounds, and presence of additives are also factors [18, 24]. Rates of biodegradation are the greatest for saturates, followed by light aromatics, high molecular weight aromatics and finally polar compounds. Increasing numbers of carbons in alkanes

(homology), variations in chain length and ring condensation account for the wide variety of hydrocarbons that occur in crude petroleum [18, 43]. Because of these variations, the biodegradability of PHCs will differ from site to site. In general, PHCs are ranked in the following order of susceptibility to biodegradation: straight chain alkanes > branched alkanes > low molecular weight aromatics > cyclic alkanes [20].

Fate of Petroleum upon Entering Soils

Petroleum waste usually enters the ground via accidental spills, leaks, or through permitted or illegal dumping [20]. Once spilled onto the soils, infiltration into the vadose zone is likely. Infiltrated soils move vertically downward through unsaturated soils, where they may dissolve into the gaseous phase, or be otherwise dispersed, diluted, or sorbed onto particulate matter, then spread out laterally over the soil water table [18, 43]. Absorption of petroleum components onto particulate matter decreases the toxicity to microorganisms, but adds to PHC persistence [20, 43]. In cases where infiltration cannot occur, for example, freezing or saturated soils, evaporation and photooxidative losses contribute greatly to PHC removal [18]. Contaminants within the vadose zone may also undergo chemical and microbiological transformations that can influence partitioning [45].

Simple aliphatic compounds are biodegraded by enzymes catalyzing oxidation, reduction, and oxidative coupling reactions. Normal alkane biodegradation is initiated by complex monooxygenase enzyme systems, which oxidize the alkane to the corresponding primary alcohol [46]. The primary alcohol is oxidized via the aldehyde to the corresponding carboxylic acid by alcohol and aldehyde dehydrogenases. Beta-oxidation enzymes convert the acid to a simpler alcohol and acetic acid. The new alcohol is further degraded with the same sequence of enzymes to form a simpler aliphatic hydrocarbon with fewer carbons [47].

The Toxic Component of Petroleum

Simple polycyclic aromatic hydrocarbons or PAHs are considered by national environmental agencies as the toxic component of petroleum. PAHs are the basis for risk assessment-based mitigation approaches for environmental remediation. They constitute by volume

only 0.2–7.0% of oil mixtures. PAHs, such as benzene, toluene, naphthalene, anthracene, and phenanthrene, and their alkyl-substituted derivatives are catalyzed by a class of enzymes known as dioxygenases. The products of initial metabolism of simple aromatic hydrocarbons are commonly catechols or substituted catechols [47]. Ring cleavage of these compounds occurs by one of two pathways depending on the species and the substrate. The ortho-pathway involves cleavage of the ring between the hydroxyl group while the meta-pathway involves cleavage of a bond between a carbon atom bearing a hydroxyl and an adjacent, non-hydroxylated carbon atom [20]. Both ortho- and meta-pathways are involved in aromatic hydrocarbon degradation, but substituted catechols are generally degraded via the meta-pathway [5].

Benzo(a)pyrene and similar high-molecular weight compounds are initially metabolized by the enzymatic catalyst monooxygenase, which converts the parent compound into a 7,8-epoxide [5]. An epoxide hydase then catalyzes the epoxides to dihydrodiols; arylhydrocarbon hydroxylase in turn transforms the dihydrodiols to phenols [35, 43]. The diastereomeric benzo(a)pyrene, 7,8-dihydrodiol and 9,10-epoxides, are presumed to be the ultimate carcinogens of benzo(a)pyrene, since they are (1) highly carcinogenic for newborn mice, (2) mutagenic and cytotoxic for both mammalian and bacterial cells, and (3) chemically reactive in binding to DNA [12].

Due to the large size and extreme insolubility of such PAHs as benzo(a)pyrene or benzo(a)anthracene, few soil/sediment microorganisms have the capability to utilize aromatic hydrocarbons containing more than three aromatic rings as the sole source of carbon and energy [48–50]. The chemical and physical characteristics of the seven key PAHs of interest are shown in Table 2.

Ex situ Approach for Soils/Sediments

Land Treatment Unit (LTU) Along an Active Railway
Rail operations have been and continue to be in the mainstream of industrial activity. Unfortunately, the use of fuels for rail operations is not without its environmental costs. At every stage of fossil fuel shipment and utilization, waste is generated and released. Ecosystems along transportation corridors have been

Bioremediation and Mitigation. Table 2 Chemical and physical properties of seven key PAHs

Compound	Rings	MW	Solubility
Naphthalene	2	128	31.70
Phenanthrene	3	178	1.0
Anthracene	3	178	0.045
Pyrene	4	202	0.132
Benzo(a)anthracene	4	228	0.006
Chrysene	4	228	0.002
Benzo(a)pyrene	5	252	0.001

MW molecular weight

Solubility (mg/L) is aqueous solubility at room temperature

damaged by exposure to the accumulation of high concentrations of petroleum hydrocarbon materials in soils and ballast material. One strategy for dealing with broadcast railroad lubricants is to apply adapted microbial consortia to the contaminated soil/ballast matrix. This procedure is called land treatment and is used to degrade waste hydrocarbons into the nontoxic, naturally occurring end products CO_2 and H_2O . Over a 12-month period, this soil remediation strategy was used to remediate diesel-contaminated soils at an active rail yard in McGehee, Arkansas. A LTU was designed and constructed to optimize petroleum hydrocarbon biodegradation rates and prevent waste mobilization into subsoils and groundwater [52, 53] (Fig. 1). The LTUs had the following features:

- Compacted clay subgrade and 40-mm HDPE (high density polyethylene) geomembrane liner leachate collection system comprised of a sand drainage layer, a gravel, and perforated pipe drain; a gravel sump and standpipe; and an 80,000-l leachate storage tank
- Leachate collection/irrigation pump, mobile sprinkler, and piping/hose
- 19-mm HDPE geomembrane cover and surface water outlet for the recycling of leachate collected from the LTU when the water content was above optimum conditions

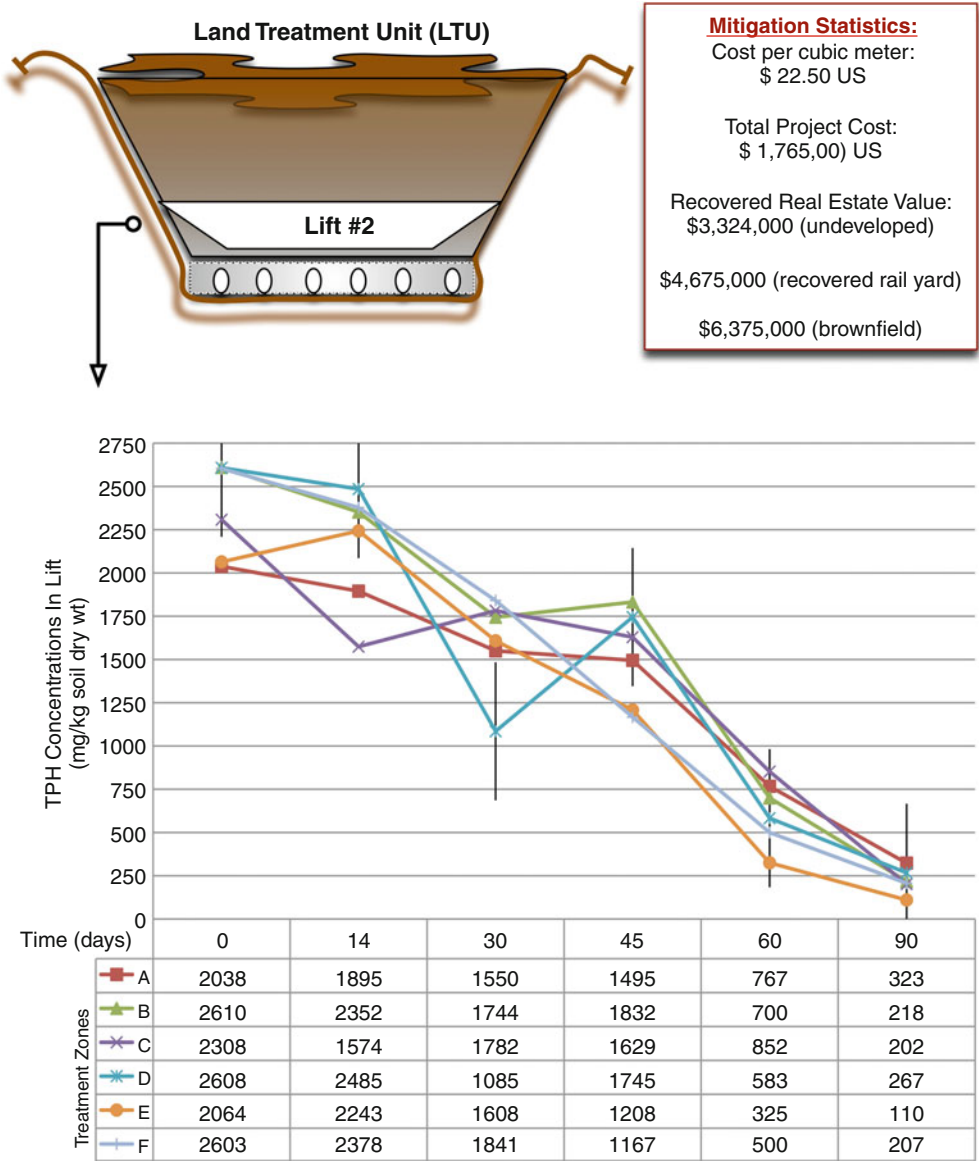
Lifts of contaminated soil/ballast layered to 0.4-m depth were loaded into the LTU and treated until a target cleanup concentration of <200 mg/kg soil

dry weight was reached. Approximately $7,500 \text{ m}^3$ of contaminated soil were successfully treated over a 6-month time frame. Soil total petroleum hydrocarbon (TPH) levels were reduced from an initial concentration of $2,500 \pm 485$ mg/kg soil dry weight to less than 140 ± 62 mg/kg soil dry weight in each of three lifts. Mean petroleum hydrocarbon reduction rates ranged from 17.3 mg/kg soil dry weight per day for cooler months to 42.5 mg/kg soil dry weight per day for warmer months. The data generated under varying climatic conditions demonstrate that the mitigation strategy of employing an adapted microbial population can be used to remediate rail TPH soils to acceptable regulatory levels for typical rail operations [55].

Ex situ Approaches for Groundwater

Recovery and Biological Treatment of Wood Preservatives in Groundwater Well-recovery networks coupled to immobilized microbe bioreactors (IMBRs) were installed at a 172-acre former wood preserving process facility in Baldwin, Florida in 1995 for the bioremediation of toxic organic wood preservatives, both free phase and soluble, present in site groundwater. The well-recovery network was designed to recover contaminated components in two steps: (1) a pumping system to remove free phase creosote from the hardpan at 10–14 m below the surface and (2) a system for recovering subsurface-clarified groundwater to a holding tank, where trace creosote fractions and pentachlorophenol were further gravity separated. Immobilized microbial isolates evaluated in earlier laboratory and field pilot tests were established into two 40,000-l bioreactors for the biodegradation of all targeted constituents [56, 57]. Microbial growth, DO, pH, flow rate and temperature were monitored in this combined in situ/ex situ bioremediation system.

The immobilized packed bed reactor (IMBR) system is filled with bio-support media, and contains adapted microbes with enzymatic capability of mineralizing the organic compounds of interest [58]. The packed bed provides a large surface area for microbial colonization [59, 60]. The bio-support media is usually a chemically inert and physically stable quartz-based diatomaceous earth material, which has a good pore morphology and high surface area. Adsorption or



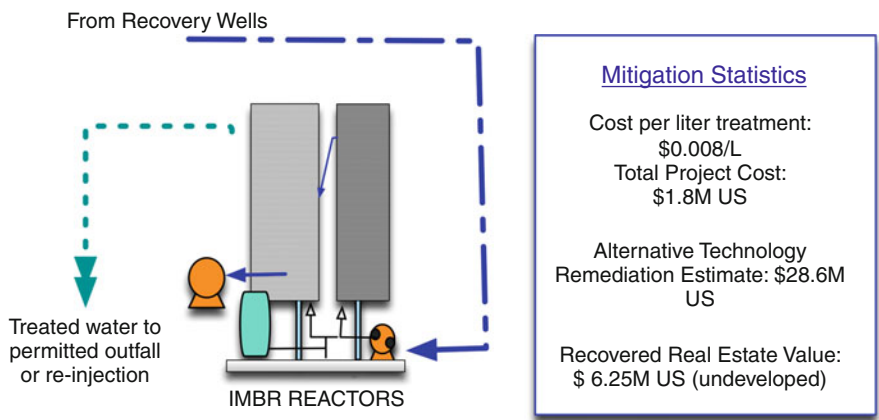
Bioremediation and Mitigation. Figure 1
Ex situ mitigation strategy for treatment of petroleum-based contamination along an active railway

covalent bonding to this media is the primary mechanism for immobilization. Bacterial immobilization involves the entrapment of cells onto the matrix. Once bound, the cells are then readily accessible to the surrounding substrate.

Ten-year operational data sets have indicated successful biodegradation of the clarified feed composed

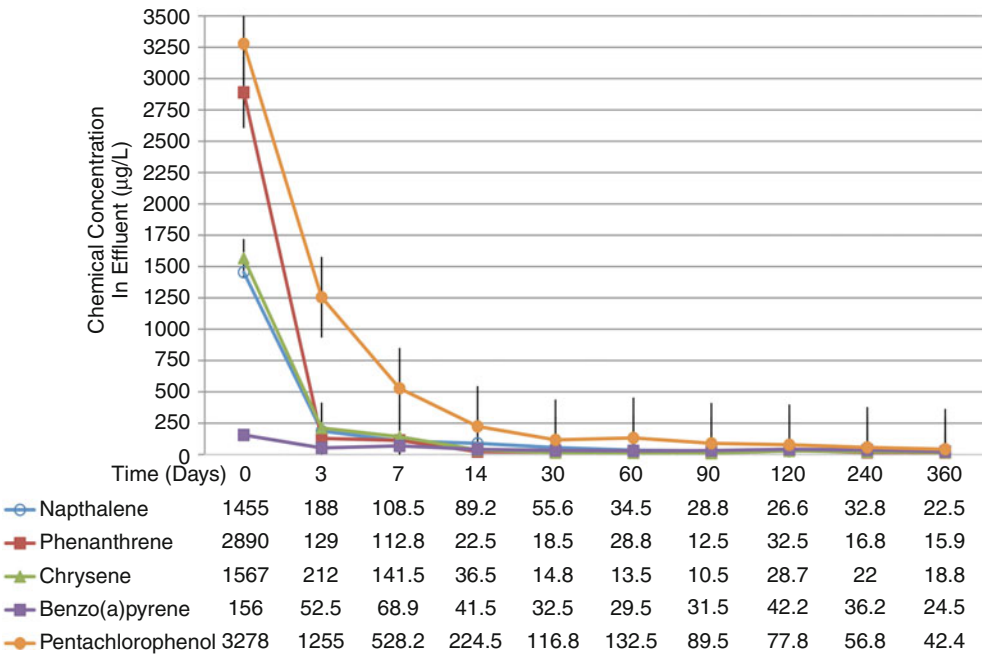
primarily of pentachlorophenol (PCP), targeted polycyclic aromatic hydrocarbons (PAHs), and minor amounts of other chlorinated phenols and nitrophenols. The recovery system retention time of approximately 3.2 days satisfied federal and state NPDES target levels (Fig. 2). Flow rates of 34.5 ± 3.8 L/min were maintained throughout the treatment time

Ex situ Bioreactor



B

Continous Biotreatment of Contaminated Ground Water



Bioremediation and Mitigation. Figure 2

Ex situ mitigation approach for continuous treatment and hydraulic control of a contaminated groundwater bloom in an urban area

frame. Treated effluent was used during drought years to irrigate surface vegetative cover and allow for percolation down to the hardpan [59]. The site received a national award in 1996 for the innovative

control and treatment of a groundwater plume from the American Forest and Paper Association. The site is currently zoned recreational and is close to meeting groundwater MCLs.

In situ Approaches for Soils, Sediments, and Groundwater

In situ remediation approaches are targeted at reducing groundwater concentrations without employing a “pump and treat” approach. Earlier technology approaches allowed for passive treatment of a contaminated plume as it moved through a biological barrier or trench. The concept has proven to be marginally successful for plume control, that is, preventing toxic groundwater from moving beyond the legal boundaries of the affected site, but does not address the real problem of the source of contamination in soils/sediments [55, 59].

Newer technologies attempt to focus treatment on the soil/sediment itself using direct addition of free microbial cells to the contaminated soil/sediment lens (bioaugmentation) or providing nutrients and allowing for the indigenous microflora to reduce soil concentrations over time. This approach, called natural attenuation, models the rate of kinetic biodegradation/mineralization of soil/sediment contamination and provides an estimate for reaching MCLs [37, 39].

A variation of both approaches is to treat the subsurface groundwater and redirect a preferred acclimated biomass to the point sources of contamination in soils/sediments. The same immobilized microbe bioreactor concept mentioned for ex situ groundwater treatment has been used for treatment of petroleum contaminated soils and groundwater, in situ. Soil seeding bioreactors called bioplugs are installed vertically using conventional drilling equipment; bioconduits are horizontally placed bioreactors installed using directional drilling equipment [61].

Adapted indigenous microbial strains are used for immobilization in the bioreactors, having been identified as able to degrade the specific compounds/contaminants of interest. The use of indigenous microflora, a concept combining the positive aspects of bioaugmentation and natural attenuation, reduces the time of microbial acclimation to surrounding soil/sediment conditions and lowers the rejection rate of viable biomass in close proximity to areas of elevated contamination. Once placed on the subsurface, the reactors contain and sustain selected microbial populations required for effective degradation of highly contaminated soils. The in situ soil bioreactors

are designed with ports for nutrient and air/oxygen amendment to maintain optimum conditions. The operational flow is maintained by initiating a pressure gradient in the reactors using compressed air/oxygen or nitrogen for anaerobic applications. The aeration flow rate is designed based on the site-specific conditions and the contaminants (volatile organic compounds or semi-volatile organic compounds) to be remediated [60, 61].

The use of contaminated groundwater or site water through the immobilized bed results in mineralization of organics in the water phase to biomass and generates whole cell bleed-off from the bed. The elevated biomass is allowed to escape from the bioplugs/bioconduits, thus introducing an enriched, adapted microflora moving layer into the surrounding soil/sediment strata in a radial pattern. Over time the biomass fronts, by physical movement and chemotaxis, infiltrate contaminated areas and reduce concentrations of chemical constituents in the soil/sediment matrix. The point source of the contaminated groundwater plume is therefore eliminated [60, 62].

Hydraulic control of the treatment area is quite important [62]. The bioplugs generate a hydraulic gradient at a targeted site, either as a result of the injection of water through the bioplugs or the injection of air, which can modify the pressure gradient. Hydraulic control generally consists of some method of collecting the water down gradient from the region of influence, that is, a recovery trench, and recycling it back to the site through the bioplugs. There are two major reasons for recycling the water: (1) recycling will control the migration of contaminants from the affected area and (2) recycling will help maintain the nutrient concentration in the injection water and reintroduce adapted microorganisms back to the affected area while treating the groundwater to meet MCLs [62].

In situ Remediation of Contaminated Groundwater and Site Soils at a Natural Gas Pipeline Compressor Station Over the last 30 years, leakage and accidental discharge of petroleum-based lubricating oil used to maintain the pipeline and related equipment of a gas transmission facility have resulted in petroleum hydrocarbon (PHC) contamination of the soil. The site evaluation conducted by a private engineering firm identified fifty areas at four different sites exhibiting

PHC concentrations greater than regulatory acceptable levels. All fifty areas were successfully remediated using bioremediation techniques. Due to the depth of the contamination and soil conditions, fifteen areas were remediated by installing approximately 550 in situ immobilized bioreactors (bioplugs) (Fig. 3a). A monitoring protocol developed for the site was implemented during the remediation period to maintain optimal conditions and make operational adjustments, as required. Only one of the areas targeted for remediation is discussed in this case study [61].

The bioplug system was designed to facilitate petroleum hydrocarbon mineralization by placing PHC-degrading microorganisms in close contact with the contaminants [61]. Initial total petroleum hydrocarbon concentrations as analyzed by EPA Method 418.1 at the subject area were as high as 16,000 mg/kg with an average concentration of 4,400 mg/kg soil dry weight. Samples were collected at different radial distances (1, 2, and 3 m) and depths (1, 2, and 3 m below ground surface) from each bioplug location within the subject area. The samples were analyzed to determine the effective radius of influence for each plug. Analysis of covariance indicated that TPH degradation at 2-, 4-, and 5-m radial distances and depths occurred at an equivalent rate throughout the degradation period [64].

Changes in polycyclic aromatic hydrocarbon (PAH) composition were monitored by gas chromatography/mass spectrometry. Samples were analyzed for PAH content and concentration. Fourteen PAH compounds were identified in varying concentrations during the day-14 sampling. By day-90, PAHs with three or fewer rings were completely degraded. However, low concentrations of flouranthene, benzo(a)pyrene, benzo(b) flouranthene, and indeno(1,2,3cd)pyrene were identified after 90 days of remediation. The presence of 4+ ring PAHs was expected because of the fact that the ability of microbes to mineralize PAHs decreases with increasing ring number [60, 62, 63].

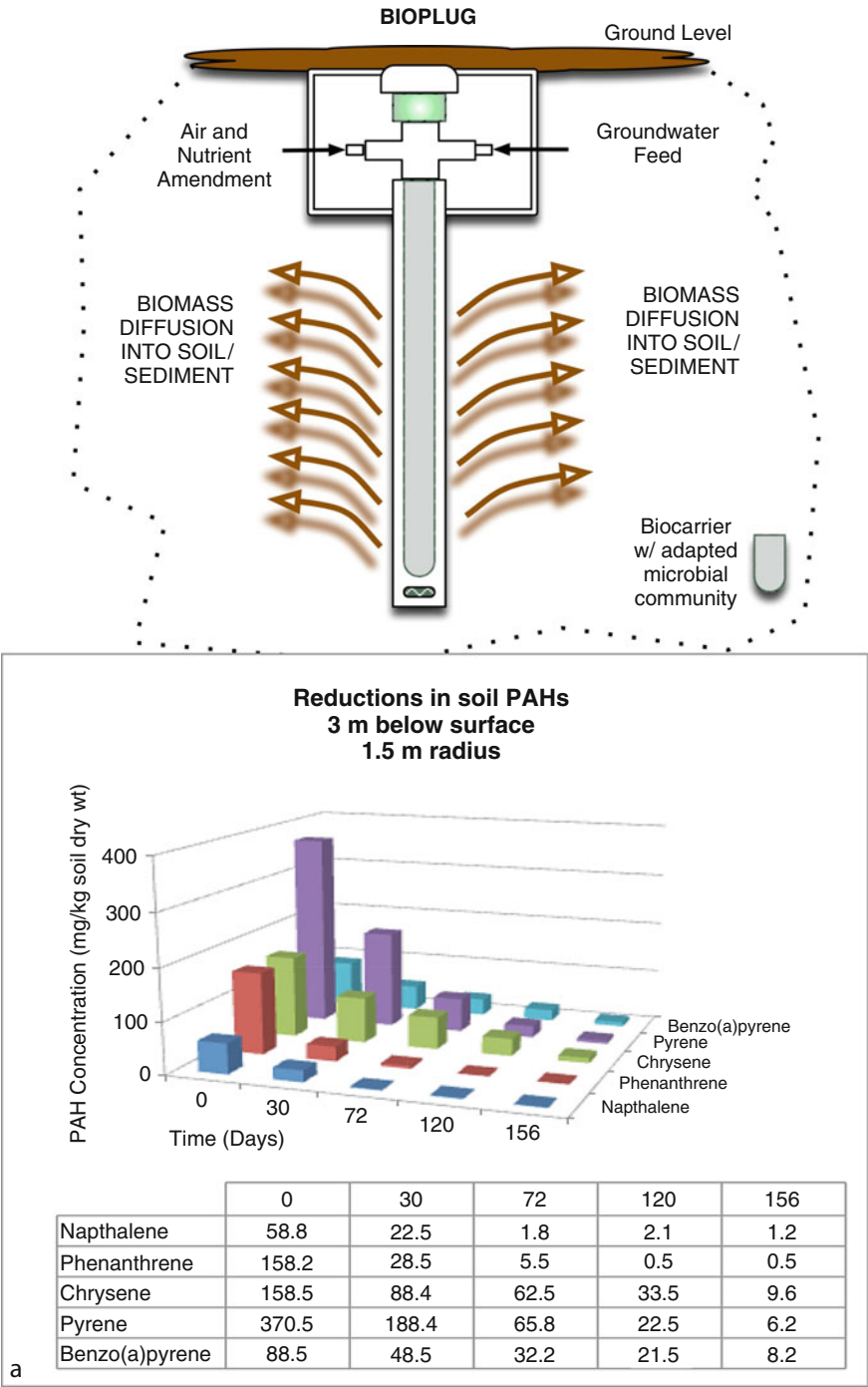
The assays were coupled with microbial measurements of total heterotrophic and total petroleum-degrading bacteria, and direct measurements using acridine orange florescent staining. Changes in the population of PHC-degrading microorganisms over time in the subject area were determined by averaging the values obtained from all samples collected within

the area. The microbial growth and the degradation of the contamination occurred exponentially within the first 30 days. The microbial growth was observed decreasing after 30 days, when the majority of the easily degraded petroleum hydrocarbons, saturated alkanes and PAHs containing fewer than three rings had been depleted (approximately by 72%). Sampling and analysis during the remediation period indicated an increase in the heterotrophic and petroleum-degrading microbial population by 75% and 57%, respectively, from day 14 to 90. Within 180 days from the activation of the remediation system, targeted compliance TPH concentrations (100 mg/kg soil dry weight) were attained. The reduction of PAH concentrations for soils and groundwater over time is shown in Fig. 3b.

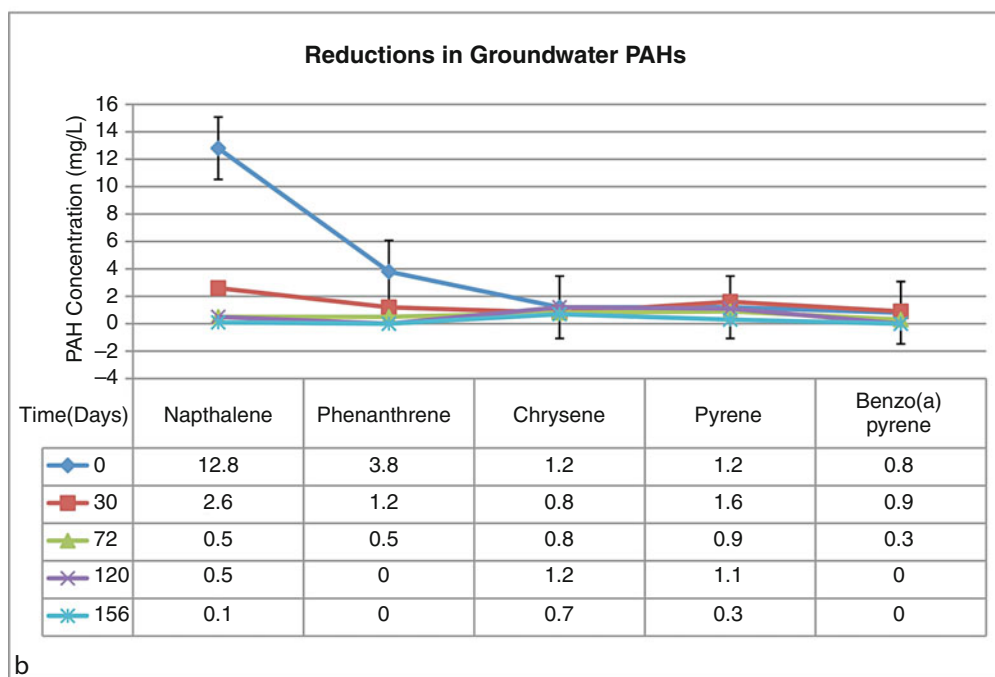
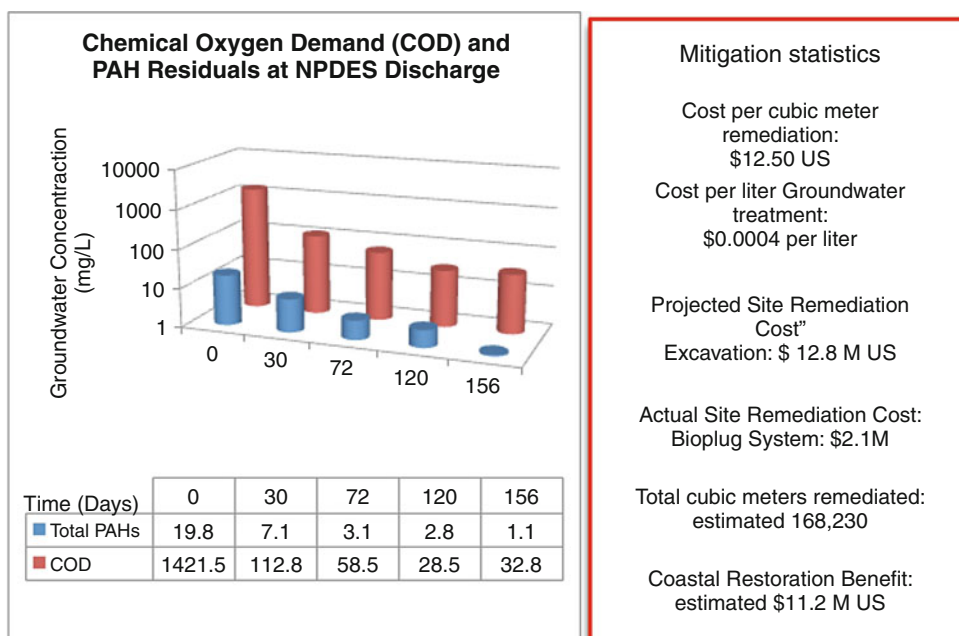
Future Directions

Improved Mitigation Drivers

In the past few years, the goal of establishing US cleanup standards using bioremediation approaches has made significant progress as cities, municipalities, state agencies, and the federal government have focused on establishing bioremediation actions linked to accepted numerical metrics within a defined cost structure or economic price tag. The US Environmental Protection Agency has used maximum contamination level goals (MCLGs) and maximum contaminant levels (MCLs) as tools for establishing the highest allowable level of contamination in drinking water [40]. With the use of the MCL rules and MCLGs, US-EPA has set in place a framework for deciding “how clean is clean” for contaminated soils and sediments and affected groundwater under the Resource Conservation and Recovery Act (RCRA) program for contaminated industrial sites and Comprehensive Environmental Response, Compensation Liability Act (CERCLA), or “Superfund,” for abandoned hazardous waste sites. Linking the MCL and MCLG criteria to “Best Available Remediation Technology,” or BART, has become the driver for risk-based bioremediation mitigation [65]. Legal judgments and records of decision (RODs) now involve decisions affecting not only environmental protection, land use, and related economics, but human health and quality of life [66]. Risk-based cleanup standards have made significant progress in the past 10–15 years; most states now have in place a series of decision tiers



Bioremediation and Mitigation. Figure 3
(Continued)



Bioremediation and Mitigation. Figure 3

(a) The application of an in situ mitigation strategy to reduce soil PAH concentrations with depth at a natural gas compressor station. (b) Reductions in groundwater PAH and total COD concentrations in a combined in situ mitigation approach to remediate a natural gas pipeline compressor station

(usually in the form of tables by specific contaminant) for assessing risk and reaching legally acceptable cleanup criteria for soil and groundwater in specific residential, light industry, or heavy commercial locations [67]. As mitigation criteria become more focused on the quality of life in determining “how clean is clean,” Risk-Based Corrective Action Plans (RBCAs) will have additional social and economic mitigation criteria separate from technical engineering and economic indices in establishing sustainable remediation cleanup standards [68, 69].

Defining Stakeholders

Over the past decade, the selection of mitigation goals and remediation technologies has been driven by technical criteria and acceptance by regulatory agencies [70]. Only in recent years has a health and health protection criteria played the more dominant role in decision making. The development of the Internet and access to information has not only affected site owners, state and municipal agencies, and board industry, but has also led to an expansion in a broader inclusion of the general public as stakeholders in any bioremediation approach. Thus the concept of sustainable remediation, practices or multitask approaches for restoring a site to its native state with a frugal use of available resources, involves stakeholders at the regional, national, and international level [70–72].

Developing National and International Bioremediation Mitigation Programs

Executive Order 13123, “Greening of the Government Through Efficient Energy Management,” by the US-EPA Office of Solid Waste and Emergency Response provided definable environmental goals for state and local municipalities in initiating sustainable mediation [65]. Smart energy resources management and green remediation can be incorporated into sustainable environmental practices. Remediation management practices of contaminated sites are outlined by Diamond et al., in which future initiatives and sustainable mitigation-based bioremediation are based [73]. State initiatives in Minnesota, California, Illinois, and Louisiana are early indications of how important federal tools are being assimilated into state and local programs [65, 74, 75]. The Canadian Environmental

Protection Act implemented in 2,000 forms the basis for establishing risk-based criteria for contaminated soil and groundwater and air blue emissions in the various provinces of the country [76, 77]. The province of Québec has made significant progress in establishing written guidelines or soil protection and contaminated site restoration. Key components of this guideline include the concept of prevention, the necessity of reclamation and rehabilitation, and most importantly the idea of the polluter pays principle. However, Québec has achieved only modest success with many sites remaining under the category of off-site disposal [77].

The European Union adopted the Environmental Technology Action Plan in 2004 to demonstrate sustainable remediation practices at specific field locations in an attempt to follow US-EPA initiatives for standardization of risk-based criteria based on human health considerations [71, 78].

Asian countries have seen record economic growth over the past 2 decades which has resulted in significant progress in quality of life improvements at the expense of the deterioration of natural resources, increased pollution, and threat to human health [79]. Japan has made significant progress with the implementation of the soil contamination countermeasures law of 2003. China and India are attempting to emulate both the US-EPA initiatives and the European Union as they struggle to make difficult public health decisions within the world’s fastest-growing economies [80].

Conclusions

One of the key axioms mentioned in Executive Order 13123 is that of “sustainability means change” [81]. Leadership at the local, state, national, and international level will be needed so as to realize the public perceptions as to what successful mitigation put into practice really means [70, 82]. Remediation selection and optimization assessments have become the norm in making good decisions for restoring impacted sites [83]. However, sustainability does not rank as the highest priority in making decisions on-site remediation. As market and government forces continue to seek economically efficient but socially responsible approaches to site cleanup, sustainability has been the driving criterion for mitigation-based bioremediation to become the norm [70].

Bioremediation mitigation strategies can be effectively designed by incorporating vadose zone and groundwater modeling [84]. Based on the availability of site hydrogeologic data and conditions, analytical modeling and/or numerical modeling can be used in designing the in situ bioremediation of the saturated zone.

An effectively designed, operated, and maintained bioremediation system offers an added advantage over conventional strategies like “pump and treat” by reducing the time of remediation. An advantage of using a technology such as the in situ immobilized bioreactors is to effectively increase the petroleum degrader population by placement of the adapted microorganisms in close contact with the organic residue. The in situ immobilized bioreactors can also be used to provide a cometabolite for degradation of hazardous by-products produced during the degradation process of some of the chlorinated solvents [57]. Also, the frequently encountered problem of ineffective indigenous microorganisms and/or low indigenous microbial population can be avoided [56].

The use of bioremediation mitigation approaches in conjunction with physical/chemical systems, that is, excavation, solidification, or vapor extraction, can provide a combination of mass reduction phenomenon and mass transfer phenomenon, thus reducing the time of remediation and the cost of cleanup. In many cases, due to the complex nature of the surface and subsurface conditions, a combination of in situ remediation techniques is recommended [83]. With rigorous engineering design, bioremediation technologies can be economical, viable, and safe solutions to real-world contamination problems [84].

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Biosensors and Bioassays for Ecological Risk Monitoring and Assessment

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Article Outline

Glossary

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Introduction

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(Whole Cells)

Future Directions

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Glossary

Analyte The molecule or microorganism that is the detection target in an analytical procedure.

Recognition element A protein or other biomolecule that can bind to an analyte with specificity and affinity.

ELISA Enzyme Linked Immunosorbent Assay. An assay using an antibody immobilized on a solid phase, (usually microtiter plate) to capture analyte and a second antibody coupled to an amplifier to detect the specific analyte.

Lateral flow assay An immunoassay in which a liquid sample is added to a dry porous carrier and wicked by capillary action to a recognition element immobilized on a specific area of the support material. A colored nanoparticle is used to detect the presence of analyte.

Nanoparticle A particle with dimensions between 1 and 100 nm.

Hapten A small molecular weight molecule (usually <1,000 Da) that cannot elicit an immune response by itself and must be attached to a larger carrier molecule prior to injection into the host animal.

Paramagnetic Magnetism induced in the presence of an externally applied magnetic field.

Definition of the Subject and Its Importance

This article describes the development and use of portable recognition element (RE)-based assays for environmental biosensing. It will focus on using portable optical biosensors; specifically surface plasmon resonance (SPR)-based biosensors for detecting a wide variety of analytes that may pose environmental risks. Portable SPR-based biosensor systems are suitable for real-time environmental monitoring as well as for many other applications including biodefense, medical diagnostic applications, food safety, and general laboratory research. Many of the detection strategies described here can also be used across other detection platforms that use recognition elements as the fundamental detection event, including lateral flow [1] and ELISA assay platforms [2].

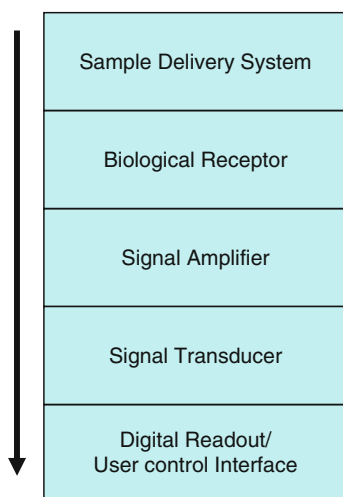
Introduction

This article will provide an overview of portable SPR biosensor applications, including a description of the fundamental technology used in SPR biosensing, the assay development process including preparation of the sensor surface for specific analyte detection, environmental sample collection, and the many different protocols and approaches used for analyte detection and signal amplification. Examples of detection of environmental pathogens and pollutants as well as the limits of detection for these examples will also be illustrated.

Biosensor Introduction

A biosensor is generally made up of four component subsystems, (1) a means to deliver the sample (fluidics system) is a requirement for most aqueous-based biosensor systems; (2) a biological sensing component (recognition element), sometimes including a signal amplifier; (3) an electronic signal transducer to convert the detection event to a signal interpretable by the user; and (4) a user interface to display the result. [Figure 1](#) shows a flow chart of a typical biosensor system. Portable SPR biosensors function by introducing a liquid sample via a fluidics delivery system to a sensor surface containing an immobilized bio-recognition element.

Most other RE-based assay systems require the addition of secondary REs attached to amplifiers to create detectable signals. Signal amplifiers include



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 1

Biosensor flow diagram. Arrow indicates the flow of information as the signal is acquired

enzymes coupled to an RE that can convert a reporter substrate into a measurable colorimetric, luminescent, or fluorescent output. Fluorometric, luminometric, or spectrophotometric readers are then required to convert the signal to digital output. SPR-based biosensors convert molecular binding events directly to a detectable signal in real time, thus a signal amplifier step is not always required for detecting the presence of analyte.

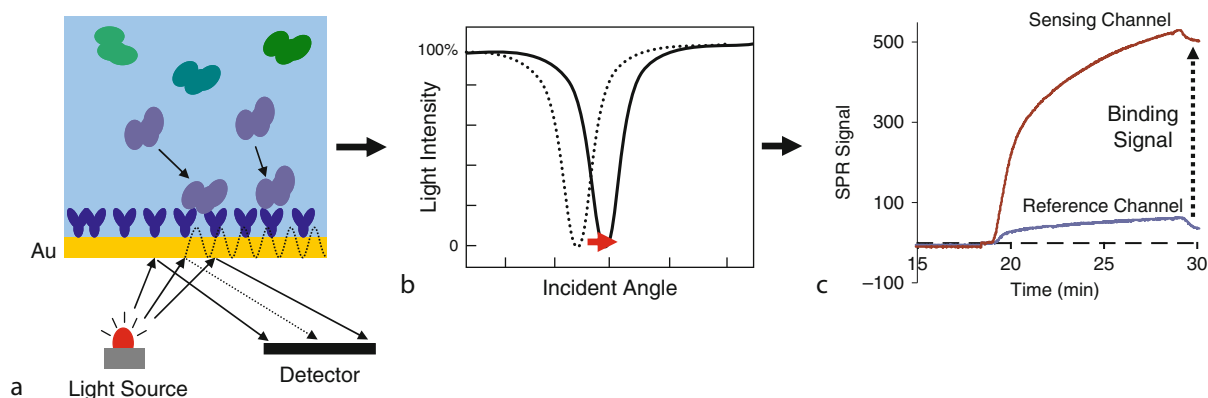
Commercial SPR systems first became available in the mid 1980s. Large bench-top instruments were developed for determining the binding rates of interaction between biomolecules in real time without the requirement for amplification. Currently most commercial SPR-based sensor systems are still used for this purpose, as well as for the study of interaction analyses in drug discovery. Detection strategies and protocols developed with bench-top SPR systems are readily implemented for use in portable devices. Bench-top SPR systems, however, are large and have delicate optical components that require sensitive calibrations and regular maintenance, precluding their use as portable devices. In addition, most commercially available SPR instruments are prohibitively expensive for use in environmental monitoring. In the late 1990s Texas Instruments developed a miniature, integrated

SPR module (Spreeta) [3–5]. The robust nature and small size of this integrated chip made possible the development of portable SPR biosensor systems. Naimushin et al. [6] described a temperature-controlled SPR system based on an early Spreeta three-channel SPR module manufactured by Texas Instruments. The importance of temperature control and the use of reference channels were noted in this publication. Chinowsky et al. [7] described a portable 24-channel SPR-based system that could detect as many as 24 different analytes. This system is based on eight miniature 3-channel Spreeta sensor chips (further described in Soelberg et al. [8]).

Principles of SPR Sensors

SPR sensors are optical sensors that exploit the interaction of light with a gold surface for the signal transduction event. Figure 2 shows the Kretschmann [9] configuration of an SPR-based detector (Fig. 2a). Polarized light illuminating a thin (50 nm) gold surface at varying angles (or wavelengths) is reflected back to a detector element (Fig. 2b). Light of a specific angle (or wavelength) is not reflected, but couples to surface plasmon electrons to generate a surface plasmon wave across the metal surface of the sensor. This coupling angle or wavelength is dependent on the refractive index (RI) of the solution adjacent to the gold surface. SPR curves are shown in Fig. 1b. The coupling angle or coupling wavelength is dependent on the refractive index (RI) of the solution adjacent to the gold surface (Fig. 2b). The reflected light intensity reaches a minimum at a specific coupling angle or wavelength. Specific recognition elements (REs) (e.g., antibodies, receptors, nucleic acids, or small molecular weight analytes) are attached to the sensor surface. The blue “Y” shapes in Fig. 2a represent recognition elements. Binding of analyte to a surface-bound recognition element causes a change in RI at the sensor surface, and a resulting shift in the SPR angle or wavelength of minimum intensity (Fig. 2c). Analyte binding is followed in real time as the system software converts the shift in the coupling angle or wavelength to an RI value as a function of time.

For a general discussion of SPR principals, the reader is referred to the following excellent books on SPR technology [10–12].



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 2

The fundamentals of SPR detection. (a) Specific analyte molecules bind to the REs immobilized on the gold surface. (b) This binding causes a shift in the coupling angle. (c) Plotting the change in coupling angle (SPR signal) as a function of real time generates a sensorgram. Red line = sensing (detection) channel. Blue line = reference (nonspecific) channel

Sensor Surface Preparation

Modifying the Gold Surface for Covalent Attachment of Recognition Elements

There are several methods for attaching recognition elements to sensor surfaces. The different approaches to surface attachment of the RE can result in different levels of interferent binding, and several attachment methods should be evaluated to determine the optimal conditions for specific assays and sample matrices. The methods outlined below will be restricted to attaching recognition elements to gold surfaces, as most SPR sensors use gold as the surface metal. Several examples of surface functionalization are described below.

Self assembling monolayers (SAMs). Various SAMs have been described for use in coupling recognition elements to gold surfaces. Most exploit the strong affinity of sulphhydryl (thiol) or disulfide groups that can interact with the gold surface to form strong and stable bonds (also called chemisorption). The sulfur gold interaction is semi-covalent with a binding energy of 45 kcal/mol [13]. For a comprehensive review of these methods, the reader is referred to [14–16].

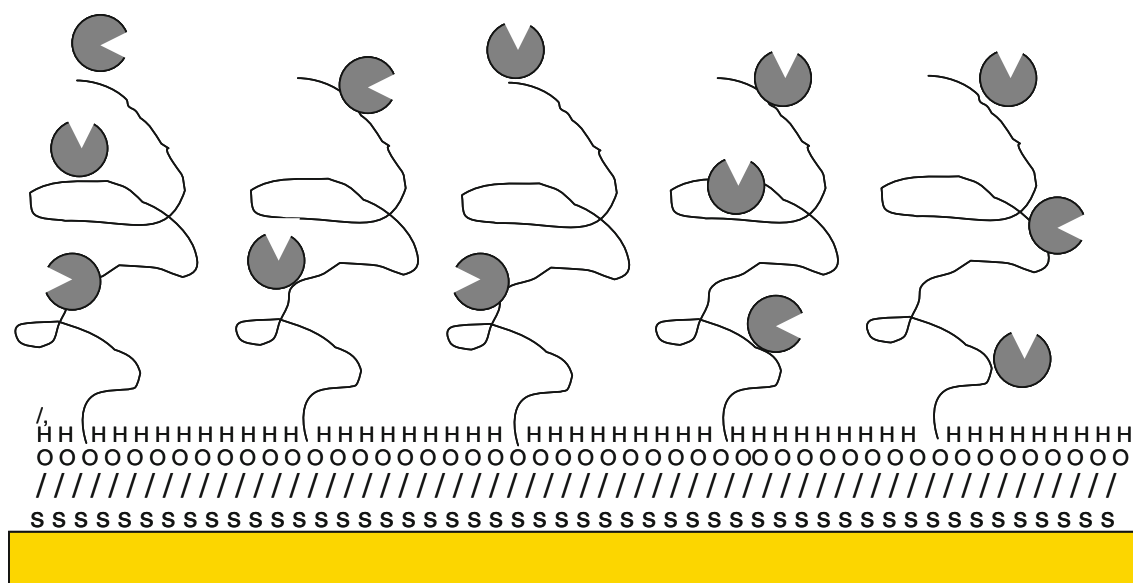
Examples of SAMs Used for SPR Sensors

Mixed alkane thiols. Alkane thiols are molecules with sulphhydryl head groups for binding to the gold surface, a carbon chain as the back bone, with a functional terminal group for attachment chemistries or

passivation. Mixed alkane thiols are terminated at the tail end with either a hydroxyl (to reduce nonspecific binding (NSB) to the sensor surface) or with a functional group (R-NH_2 or R-COO^-) at a fixed percentage to allow even spacing of the functional groups to which an RE can be attached by standard coupling chemistries. For example, EDC/sulfo-NHS activate surface carboxyl groups, which in turn couple to amine groups of the RE [17]. Attachment of the alkane thiols to the gold surface is achieved by soaking the clean gold surface in mixtures of alkane thiols [18].

Hydrogel surfaces. One of the most widely used SPR surfaces is a carboxy-dextran hydrogel to which multiple receptors or ligands can be attached per strand of dextran [19, 20]. This protocol has the advantage of a fairly dense three-dimensional decoration of the sensor surface with receptors or ligands, but can have issues with bulkier analytes since the matrix can slow mass transfer to the receptors located throughout the hydrogel matrix. The carboxy-dextran layer can be built on a SAM to form a very stable surface for protein or ligand immobilization (Fig. 3).

Gold-binding peptide (GBP). GBP is an engineered protein domain with repeat sequences that binds tightly to gold surfaces [21]. This small peptide can be used as a foundation layer on the gold surface to which REs can be attached via standard EDC-NHS protein coupling [17]. A description of the protocols involved



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 3

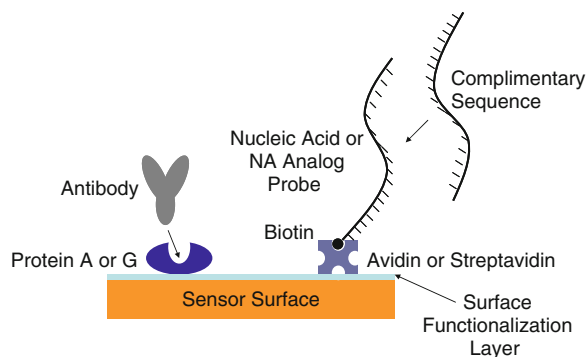
Alkane thiol with terminal OH groups and functional groups with recognition elements attached

in using the gold-binding peptide for sensor surface preparation can be found in Woodbury et al. [22].

Physical adsorption of recognition elements. Antibodies and other proteins can also be directly adsorbed (also called physisorption) through charge interactions between the gold and protein surfaces without specific chemical modification. For this procedure, antibodies in solution are simply introduced in concentrated form (>1 mg/mL) to a gold surface cleaned with nitric acid and ethanol. The orientation of the antibody is not controlled in this procedure; therefore not all the antibodies will have the functional arms oriented outward. However, this method has been shown to produce a surface that is robust and capable of sensitive detection and regeneration [7]. This simple approach to surface coating can be useful for many sensor applications.

Covalent attachment of recognition elements to modified sensor surfaces. Sensor surfaces modified by SAMs terminated with free amino or carboxyl groups can then be modified to covalently couple recognition elements (e.g., protein molecules) through standard protein coupling procedures. The most commonly used reaction is the amino to carboxyl protein coupling using the chemicals EDC or EDC/sulfo-NHS for carboxyl group activation and protein coupling [17].

Attachment of “adapter molecules.” Generic surface foundation layers may be attached by adsorption or covalently coupled to SAM-modified sensor surfaces followed by binding of the RE to generic adapter molecules. Some examples of these generic receptor molecules include avidin or streptavidin to which can be attached biotin-labeled recognition elements such as antibodies, DNA, protein nucleic acids (PNAs) [23], locked nucleic acids (LNAs) [24], ligand receptors, or other biotin-labeled recognition elements [25] (Fig. 4, Right). Other types of receptors that can be attached to the sensor surface include proteins A or G. The bacterial proteins A and G that bind specifically to the Fc domain of immunoglobulins (Igs) (most notably many IgGs) can be adsorbed or covalently attached to a modified gold surface and used for construction of regenerable sensor surfaces for repeat assays. These surface-adsorbed molecules provide “sockets” for antibody binding to sensor surfaces. The Igs can be removed with regeneration buffer (e.g., low pH), and new antibodies, for example, with different specificity, can be added to the surface “sockets” (see Fig. 4, Left) [26, 27]. Covalent attachment of antibody receptor molecules to robust surfaces such as SAMs should provide longer-lasting regenerable surfaces.



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 4

Adaptor molecules allow for replaceable antibody surface (left) or binding of biotinylated probes (right)

Surface functionalization for competition assays. For the competition-based assays described below in the section entitled “Small Molecule Detection,” small molecular weight ligands are often conjugated directly to a SAM surface or to a carrier protein [28, 29] that can either be covalently attached to a SAM, adsorbed to the sensor surface, or chemically coupled to a surface foundation layer in a similar manner as with the antibody attachment protocols.

Surface passivation with blocking proteins. Another important aim in preparing a sensor surface for analyte detection is to generate a sensor surface that has a low degree of nonspecific, or background binding from the sample. Additional steps to passivate the sensor surface and minimize nonspecific binding may be required after attaching the RE [30]. For example, when analyzing a serum sample, proteins may nonspecifically bind to the sensor surface and interfere with or overwhelm the analyte-specific binding signals. By pretreating the sensor surface with serum proteins such as albumin or other blocking agents, nonspecific sample matrix proteins can be blocked from interaction with the sensor surface.

Referencing

Referencing is another way to compensate for the effects of nonspecific interactions in bioassays. Referencing involves monitoring an additional channel with an RE that is not specific for the analyte of interest. It is important to include a reference channel with the

same antibody type, such as a rabbit polyclonal or mouse monoclonal, and use the signal from this channel to correct for nonspecific binding. In the example shown in Fig. 2c, the light blue line shows that there was little nonspecific binding signal during the sensing step. With proper reference channel treatment, subtraction of the reference channel value from the signal of the analyte-specific channel provides an accurate measure of the specific binding.

Sensor Storage and Preservation

It is important to make use of stable recognition elements and to develop protocols for maintaining activity of the sensor REs during storage. There is relatively little information in the literature regarding preservation of recognition elements on sensor surfaces. Drying a specific carbohydrate glass such as a trehalose and high molecular weight dextran layer over the RE has been shown to preserve antibody function for at least 1 year without the need for vacuum packing the sensor element [28].

Sample Acquisition from the Environment and Removal of Interferents

SPR-based biosensors for environmental monitoring require that the analytes are contained in an aqueous solution, often with some preprocessing to concentrate the sample and/or reduce the level of interferents and enhance the specific signal from the target analyte. The protocols for sample collection/processing are highly dependent on the target analyte and the sample matrix. An environmental sample will generally fall into one of three general classes: sample in liquid form, sample in solid form, such as in dirt or on a solid surface, and sample dispersed in air, such as aerosolized pesticides, microbes, or nerve agents. Once the sample is collected or transferred to an aqueous phase, it can be delivered to the biosensor for detection of the specific target analyte.

Airborne samples. For bioaerosols and airborne chemical samples, a number of collection systems have been described or are commercially available. Because the immunoassay SPR-based assays depends on the sample being in liquid form, the two most practical collectors for this medium are wetted-wall cyclonic collectors [31] and glass impingers [32, 33].

Samples can also be obtained by directing air flow through a filtration system; however the filter must be stripped with aqueous buffer to suspend the trapped particulates for analysis.

Bioaerosol wetted-wall cyclone collectors are those in which air samples are directed over a high-surface-area sample collecting liquid making use of cyclonic action. Environmental sampling using a cyclonic collector to analyze long distance airborne transport of both viral and bacterial porcine pathogens was demonstrated by Dee et al. [31]. In their example, aerosolized porcine reproductive and respiratory syndrome virus (PRRSV) and *Mycoplasma hyopneumoniae* were collected using a liquid cyclonic collector from as far as 4.7 km from the source of the swine pathogens.

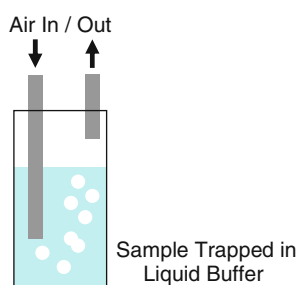
Glass impingers are the simplest types of air-to-liquid sample collectors. Impingers are commercially available and operate by simply directing a stream of air into a liquid sample (Fig. 5). There are a number of examples in the literature of using impingers for collecting airborne particles into a liquid for analysis, including for the detection of airborne nitrophenols (see, e.g., Bishop and Mitra, 2007) [32] and airborne bacterial spores dispersed in an aerosol chamber (see, e.g., Rosen, 2006) [33].

Filter sampling and resuspension in liquid medium is another approach to sample introduction for environmental biosensing. In these samplers, an air or water stream is driven through a filter device, and the filter will trap the small target analyte particles. Mixed cellulose ester (MCE), Teflon, poly-tetra fluoroethylene (PTFE) filters, and gelatin filters can trap particles such as bacteria and viruses from aerosolized or aqueous

samples. The concentrated samples are then suspended in an aqueous solution for analysis. Fabian in 2009 [34] demonstrated a comparison of four aerosol collectors, including two types of filter collectors (gelatin and Teflon) for airborne influenza virus collection and viability analysis. Burton et al. in 2005 [35] compared the MCE, PTFE, and gelatin filter materials for detection of the *Bacillus anthracis* stimulant *B. subtilis* in bioaerosols. Filtration in which the filtrate is analyzed for specific molecules or organisms smaller than the filter pore size can also be employed. Figure 6 shows an example of a small molecule detection filter device that excludes larger protein molecules in a saliva sample, and smaller molecules that pass through the filter are then delivered to a sensor surface [29]. This approach has the advantage of eliminating components of the matrix that may bind nonspecifically to the sensor surface, such as mucins in saliva or biofilm forming molecules from seawater.

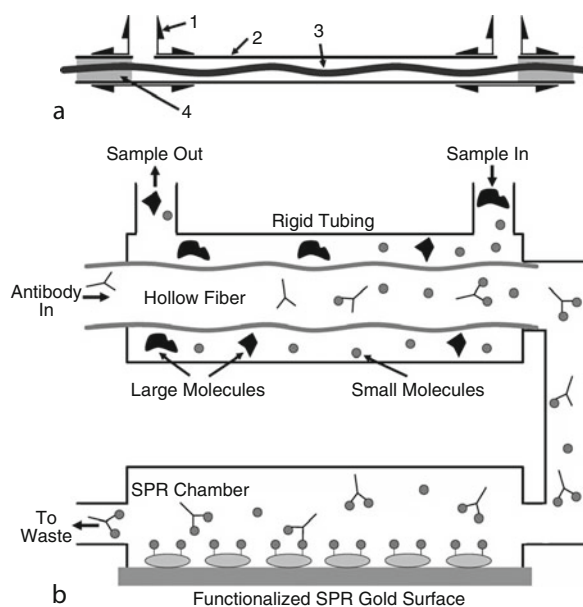
Liquid samples. Samples already in liquid such as freshwater or seawater samples are relatively easy to process and are amenable to processing with automated systems. Liquid collection systems can be as simple as a collection tube dipped by hand into the water for manual collection or a pump delivery system to the sensor. Filtration can also be an efficient way to collect a sample if the analyte of interest is large enough to be trapped with a filter. For example, *Giardia duodenalis* and *Cryptosporidium* species present in low levels in drinking water were filtered and detected via polymerase chain reaction (PCR) by Plutzer et al. [36]. In cases where the analyte may be present at low concentrations or where the matrix may contain many interferences, filtration can be a way to concentrate samples and select for specific sizes of particles through low or high molecular weight cutoff filters. The analytes can be washed from a filter with a buffer that is optimal for detection, or a hollow fiber flow-filter can be used to change out buffer conditions in real time (Fig. 6). More complex ocean sample collection makes use of a suspended-particle multi-sampler (called a rosette) for obtaining discrete samples from given depths and locations [37].

Solid surface samples. Collecting environmental samples from surfaces for analysis can be as simple as swiping the surface with a moistened swab. The swab can then be added to a liquid buffer solution and



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 5

Glass impinger for converting aerosolized samples to aqueous samples



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 6

An example of in-line filtration of samples to remove interferences before competition assay analysis with a portable Surface Plasmon Resonance biosensor. External, in-line filtering flow cell, which directs flow into the SPR system. **(a)** Construction of the in-line filtering flow cell required sliding a 1.6-mm Tee connector (1) (T210-1, Valve Plastics, Fort Collins, CO) over the ends of 0.75-mm inner diameter PEEK tube (2) (1533, Upchurch Scientific, Oak Harbor, WA), followed by drilling a hole into the PEEK tube to allow sample flow, and then sealing the PEEK tube to the tee with urethane adhesive (Lord Corp., Cary, NC). A hydrophilic hollow fiber (3) (Minntech, Minneapolis, MN) with a molecular weight cutoff of 20,000 was inserted into the PEEK tube, and both ends were sealed with urethane adhesive (4). Following sealing of the hollow fiber into the PEEK tube, the ends of the hollow fiber were cut flush with the tee preserving the opening to the hollow fiber. **(b)** Salivary samples were diluted 1:2 with buffer and flowed through tubing external to the hollow fiber. The antibody solution was flowed countercurrent through the hydrophilic hollow fiber and then through the SPR biosensor system. Diffusion may also be aided by bulk flow across the hollow fiber wall controlled by a pressure differential created by higher flow rates outside the hollow fiber (not drawn to scale). (From [29])

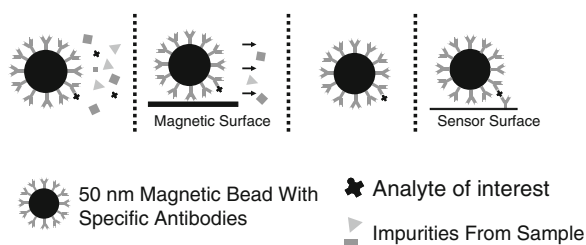
vortexed to resuspend the sample in liquid. Particulates such as soil samples can be measured or weighed, then resuspended in liquid buffer. In “Surface Sampling of Spores in Dry-Deposition Aerosols” Edmonds et al. compared different swab materials used on four surfaces with different surface properties for sampling of bacterial spores [38]. Once the target analyte(s) has been collected in or transferred to an aqueous solution, a number of different strategies have been used for the specific detection of the target analyte. These strategies are outlined in the following section.

Immunomagnetic Particle Purification of Specific Analyte

Paramagnetic antibody-conjugated particles can be used to rapidly concentrate and purify an analyte from a complex matrix of particles commonly found in environmental samples. Figure 7 shows an example of this type of cleanup procedure. Immunomagnetic beads (IMBs) decorated with analyte-specific antibodies are added to a sample and mixed. The IMBs bind the analyte of interest, then are immobilized in a magnetic field, and all impurities and potential interferences are washed away with analysis buffer. The IMBs with bound analyte in analysis buffer are then released by removal of the magnetic field and introduced to the sensor for detection [8]. Once the concentrated, purified target analyte(s) is collected in or transferred to analysis buffer, a number of different strategies have been used for the specific detection of the target analyte. These strategies are outlined in the following section.

Detection Strategies

Development of an SPR-based assay requires consideration of several factors that will affect the SPR signal: (1) the type and properties of the surface-immobilized recognition or specificity element; (2) size of the analyte of interest, reflecting its ability to generate a RI change large enough to be detected when bound by the RE immobilized on the sensor surface; (3) the specificity of the recognition element for target analyte and related analytes; (4) strategies for reducing nonspecific binding of other components of the matrix, and (5) any strategy for amplifying the signal from bound analyte.



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 7

Magnetic bead cleanup of sample matrix. Each frame (separated by a dotted line) is a separate step in the cleanup and detection process

Properties of the recognition element. A recognition element is any molecule that can bind with high specificity and affinity to the target analyte. The recognition element should be stable and ideally be capable of regeneration for many cycles of analyte binding and surface regeneration. Antibodies have been found to fulfill these requirements and have been used for many different sensing applications [39]. Receptors with high specificity and affinity for analyte such as metallothioneins binding to heavy metal ions (Cd^{2+} and Hg^{2+}) can also serve as suitable recognition elements [40]. The use of molecular imprinted polymers (MIPs) can also be used, for example, ochratoxin A, an *Aspergillus* that produced mycotoxin, was detected with a MIP surface with SPR at concentrations down to 0.05 ppm [41]. Nucleic acids or nucleic acid analogs such as peptide nucleic acids (PNAs) can be used on a biosensor surface to detect complementary sequences of nucleic acids such as ribosomal RNA (rRNA) from *Escherichia coli* [42]. Locked nucleic acids (LNAs) are other analogs with increased thermal stability and resistance to nuclease activity, which can also be used as recognition elements for detection of DNA or RNA [24].

There are several issues to consider when preparing an SPR sensor surface for the detection of a specific analyte. First, the recognition element that is attached to the sensor surface should be very specific for the target analyte. This specificity is often provided by the immobilization of an antibody raised with against all or part of the target analyte. Specificity can be determined by testing the antibody for cross reactivity with closely

related molecules or microorganisms. It is important to test the specificity of the chosen recognition element against analytes with structures similar to those of the target analytes, particularly if related analytes may be present in the sample matrix. For example a bacterial antibody raised to *B. anthracis* spores can be tested against other *Bacillus* species for cross reactivity. This example is demonstrated in the multi-analyte detection shown in Fig. 13. Here *B. subtilis* (BG) spores are tested against *B. anthracis* spores, and against many other unrelated antigens. The specificity of the antibody for the bacterial analyte of interest, but not for a closely related bacterial species, is shown in this figure. The extent of cross reactivity with other antigens, especially related antigens, determines usefulness of a given antibody preparation for specific applications.

REs with high affinity are also desirable for achieving high sensitivity of analyte detection. Antibody target affinities can vary by as much as four orders of magnitude [43]. SPR and ELISA analysis can be used for determining the antibody association and dissociation rates (K_a and K_d) and thus determine the usefulness of the antibody for high sensitivity detection assays [44]. For example, SPR can be used to screen for high affinity monoclonal antibodies from a pool of different clones [45, 46]. The primary goal when developing a detection assay is to have a sensor surface that binds the target with very high affinity and specificity without binding other interferences present in the sample matrix.

Consideration of antibody properties and purity. The choice of an analyte-specific antibody may require evaluation of several different polyclonal or monoclonal antibody preparations. Significant differences in both specificity and affinity of analyte binding will greatly affect the ability of a given protocol to provide the levels of sensitivity and specificity required for a given application. Often, it may require the generation of monoclonal or polyclonal antibodies to the target analyte if the appropriate antibodies are not available from commercial sources or from collaborators/colleagues. An additional factor affecting the quality of signal is the extent of purity of the antibody being used for the assay. It is important to note that with a surface interaction method such as SPR, the greater the purity of the specific antibody on the SPR surface, the more robust will be the response to analyte binding.

Affinity purified polyclonal or monoclonal antibodies are essential for optimal SPR-based protocols. When making use of amplification protocols, either monoclonal or polyclonal antibodies, or monoclonal antibodies with different epitope specificity may be useful. The amplification antibodies may be of lesser purity since any unrelated antibodies will wash through the system. Similar considerations will be obtained for other types of recognition elements.

Detection Limit by Analyte Type

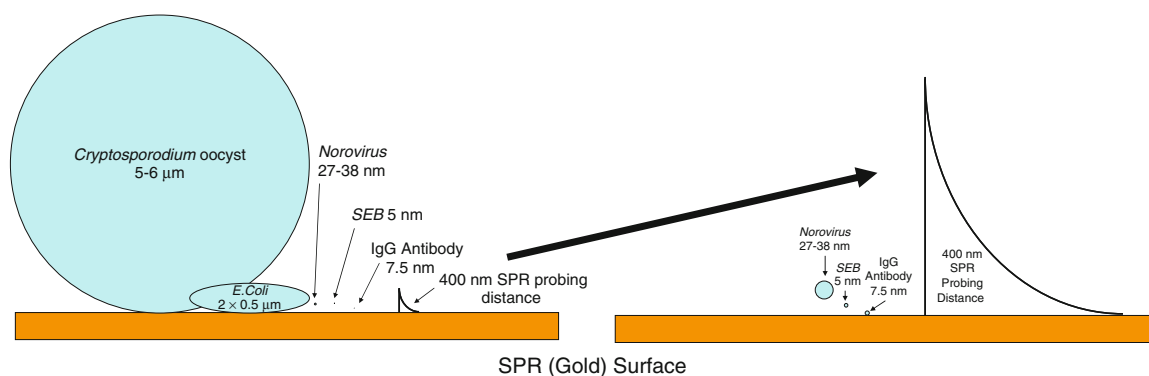
Once a suitable recognition element has been acquired, the next step is determining the detection limit for the analyte of interest. Dividing analytes into four general classes is helpful for discussion. The categories of analyte detection with SPR are usually broken down into groups based on size. Small molecules do not usually affect generate a significant change in RI directly when bound to the sensor surface; very large analytes (e.g., whole cells) can be larger than the effective probing range of the plasmon wave, and thus only a fraction of the particle will affect the SPR signal. The categories for detection are usually classified as (1) small molecules such as organic pollutants, chemical toxins, and heavy metals (below MW 5,000) [14, p. 476] usually undetectable by direct SPR measurement (2) protein molecules >5,000 Da (e.g., protein toxins, protein biomarkers, or antibodies), which diffuse easily and are large enough to generate a significant surface change in RI, (3) viruses, and larger particles such as (4) microbes, and (5) single-celled eukaryotic organisms (algae and

fungi). Whole cells, whether bacteria or eukaryotes, often diffuse slowly to the sensor surface, may not bind easily to surface recognition elements due to shear forces, and fall at least partly outside of the penetration depth of most SPR instruments (approximately 100–600 nm) [14], p 463. Figure 8 shows the sizes of several proteins and microorganisms relative to the antibody surface and SPR penetration depth. A *Cryptosporidium* oocyst [47], an *E. coli* cell [48], a norovirus particle [49], an SEB protein toxin molecule [50], and an IgG detection antibody [51] are displayed in relation to the probing distance from the SPR surface.

Small Molecule Detection

Direct detection of small molecules with SPR. There are a few examples of SPR biosensors being used to directly detect the binding of metal ions. Wu et al., 2004 [52] used the heavy metal binding protein metallothionein immobilized on an SPR surface as a sensor for metal ions such as cadmium (Cd^{++}), zinc (Zn^{++}), and nickel (Ni^{++}). With this system, concentrations of Cd^{++} as low as 2 μM were detectable.

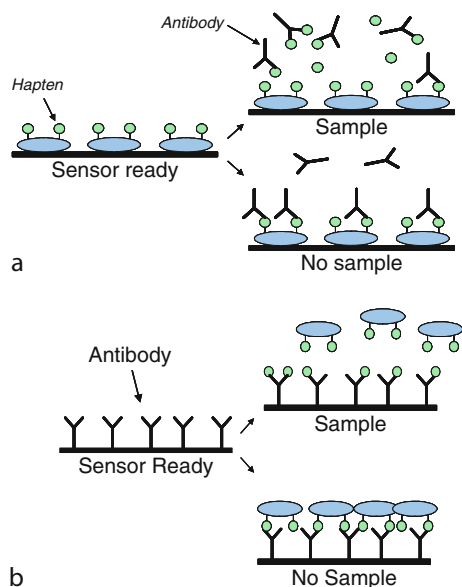
Competition (inhibition) for detection of small molecules. Since the binding of small analytes does not generally result in large changes in RI at the sensor surface, detection of small molecular weight analytes often makes use of an indirect assay in which the analyte itself is immobilized on the sensor surface,



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 8

Some examples of the size variation of different classes of analyte detectable by SPR biosensor assay compared to the effective detection range of an SPR sensor

often through coupling to a carrier protein or tethered to the surface covalently. The most common method of antibody-based detection of small molecules is referred to as a competition or inhibition assay. The target analyte (hapten) molecule is attached to the sensor surface using one of the protocols described above in the sensor surface preparation section. Antibody in solution is then allowed to bind to the surface-immobilized target analyte, establishing a rate of antibody binding in the absence of analyte. Samples containing the target analyte are introduced, inhibiting antibody binding at levels proportional to the concentration of target analyte in the sample (Fig. 9a). As an alternative to rate determination, total binding signal can also be measured, and this signal is also inversely proportional to the concentration of analyte over



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 9

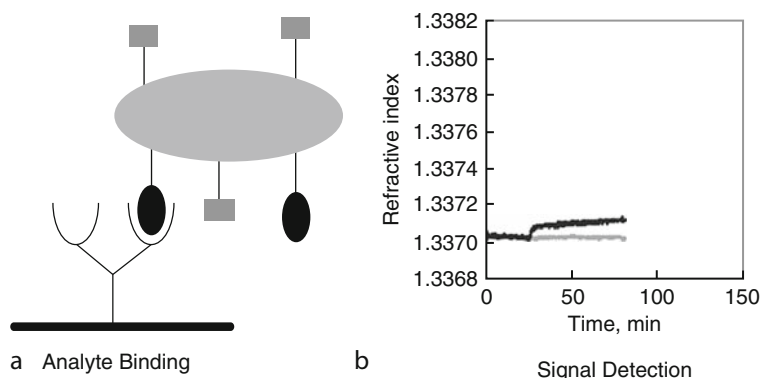
(a) Competition detection of a small molecule using SPR. A schematic of the sensor surface shows the hapten-conjugated protein on the surface of a sensor in the "sensor ready" state. The quantity of antibodies that bind to the surface during exposure to sample is inversely correlated to the amount of analyte in the sample. **(b)** Alternatively, small molecule binds to the antibody on the sensor surface and inhibits binding of the larger carrier protein derivatized with the same small molecule. This protocol will conserve antibody if it is costly or scarce

a specific concentration range [53]. Another protocol (Fig. 9b) can be used in which anti-analyte antibody is immobilized on the sensor surface. With this protocol, sample containing the small molecule is first added and allowed to bind to the surface antibody. Analyte-protein conjugate is then introduced to the surface. The signal from this binding step is again inversely proportional to the amount of analyte bound to the surface from the original sample. This protocol is beneficial when antibody needs to be conserved due to low availability or high cost.

There are many examples in the literature of small molecule detection using the competition assay. For example, domoic acid (MW 311), a toxin produced by the algae *Pseudo-nitzschia* that can accumulate in marine filter feeders, was detected using a competition assay in both laboratory buffers and in spiked clam samples at levels as low as 4 ng/mL [28]. Yu et al. [53] described a domoic acid competition assay with a detection limit of 0.1 ng/mL in laboratory buffers using an SPR-based detection system. The organophosphate insecticide chlorpyrifos (MW 250) was detected in a variety of environmental water samples by SPR using a competition assay with a detection limit of 45–64 ng/mL [54]. TNT (Trinitrotoluene), a component of land mines and other explosive devices (MW 227) was detected by SPR analysis at concentrations ranging from 0.008 ng/mL (8 ppt) to 30 ng/mL (30 ppb) [55].

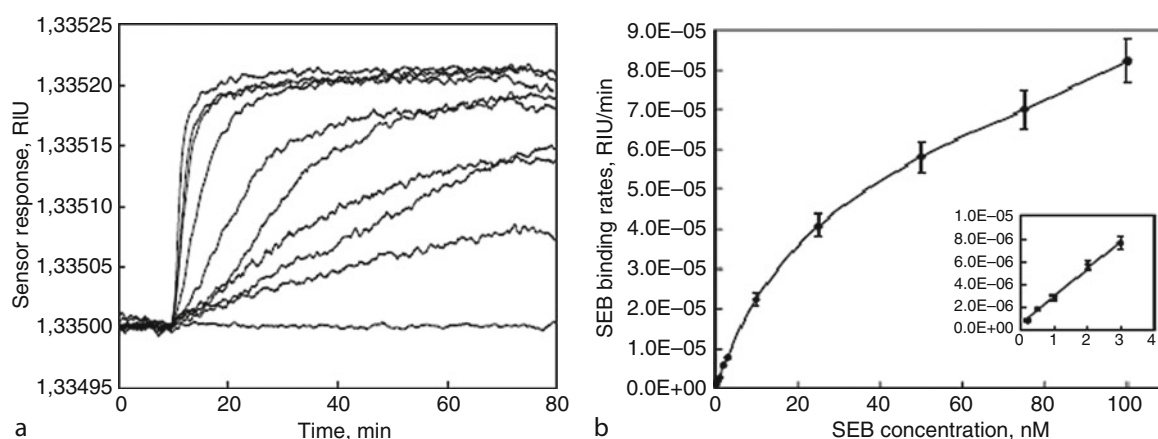
Direct Detection of Protein Analytes

One of the primary advantages of SPR-based systems is the ability to detect direct binding of analytes quickly and without amplifier reagents or other manipulation of the sample (Fig. 10). If the concentration of a larger analyte (>5,000 Da) such as a protein toxin is at an adequate level, and if there are not significant interferents in the sample, it is possible to not only directly detect the analyte, but also to quantify the analyte from either the initial rate of binding or the maximum shift in RI on binding of the target analyte to the surface RE. Figure 11 shows the direct detection of *Staphylococcal* enterotoxin B (SEB) in buffer solution at several different analyte concentrations [56]. At low analyte concentrations (Fig. 11b, inset), the concentration of analyte is linearly dependent



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 10

(a) Binding of protein analyte to antibody immobilized on the gold sensor surface. (b) Real-time signal (refractive index) generated during the binding event



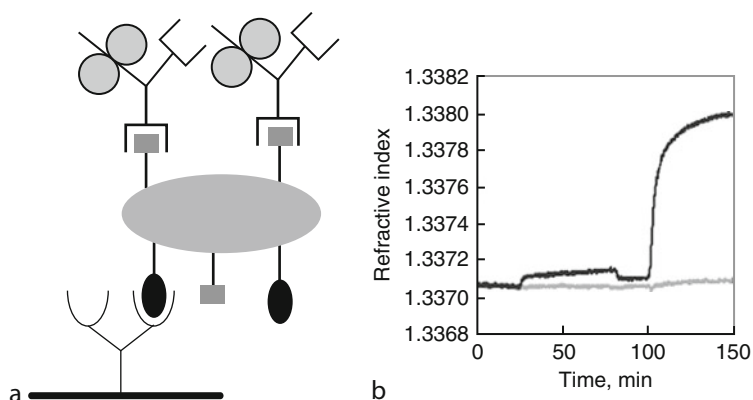
Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 11

(a) Binding of *Staphylococcal* enterotoxin B (SEB) to sensor surface at different concentrations of SEB (0.2, 0.5, 1, 2, 3, 10, 25, and 75 nM). (b) Plot of initial rates of binding of SEB as a function of SEB concentration (inset, expanded scale for the indicated low concentrations of SEB). (From [56])

on the initial rate of binding of SEB to the surface-immobilized antibodies.

Amplification strategies. Amplification is generally carried out with addition of a second recognition element prior to or after the analyte is bound to the surface (Fig. 12). Also called a sandwich assay, this second element can be an antibody, or an antibody coupled to a larger particle to affect a greater increase in the SPR signal. Sensitivity of analyte detection can be dramatically increased by using amplifiers. Proteins, including antibodies like the fish iridovirus antibody [57], microbial toxins (SEB) [56, 58], and many others are detected with amplification steps to increase the binding signal.

To increase the sensitivity of detection and at the same time validate the identity of analyte, a second, particle-bound antibody specific for an analyte epitope different than that of the surface-immobilized antibodies may be used. Nano-immunomagnetic particles or nano-gold particles have been used for this application. The advantage of the nano-immunomagnetic particles is that they may be used in sample processing steps to purify and concentrate the target analyte before introduction to the sensor [8]. Figure 13 shows an integrated amplification protocol, where the SEB is bound first to a magnetic particle and then allowed to bind to the SPR surface. The resulting signals for 10 ng



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 12

(a) Binding of secondary antibodies with different epitope specificity coupled to amplifier particles to captured analyte. (b) Signals generated upon binding of analyte to the sensor surface followed by binding of the secondary antibody/bead complex

and 1 ng/mL SEB are much larger than SEB alone. These amplifiers can be the same magnetic particle used for purification of the sample shown in Fig. 6. The concentration/purification step provides a significant increase in the sensitivity of the detection protocol and eliminates possible interferences from the sample stream at the same time. Larger micron-sized particles conjugated with the secondary antibodies diffuse too slowly to the sensor surface to be useful in real-time detection. Nano-gold and nano-magnetic particles can also be coupled to nucleic acids for amplification of DNA or RNA binding to a sensor surface. A sulfur group-derivatized nucleic acid or a biotinylated nucleic acid can be attached to the gold or magnetite particles.

This sandwich protocol is useful for the detection of microbes, spores, viruses, and toxic proteins [7]. Figure 14 also shows sandwich type amplification of several different types of analytes.

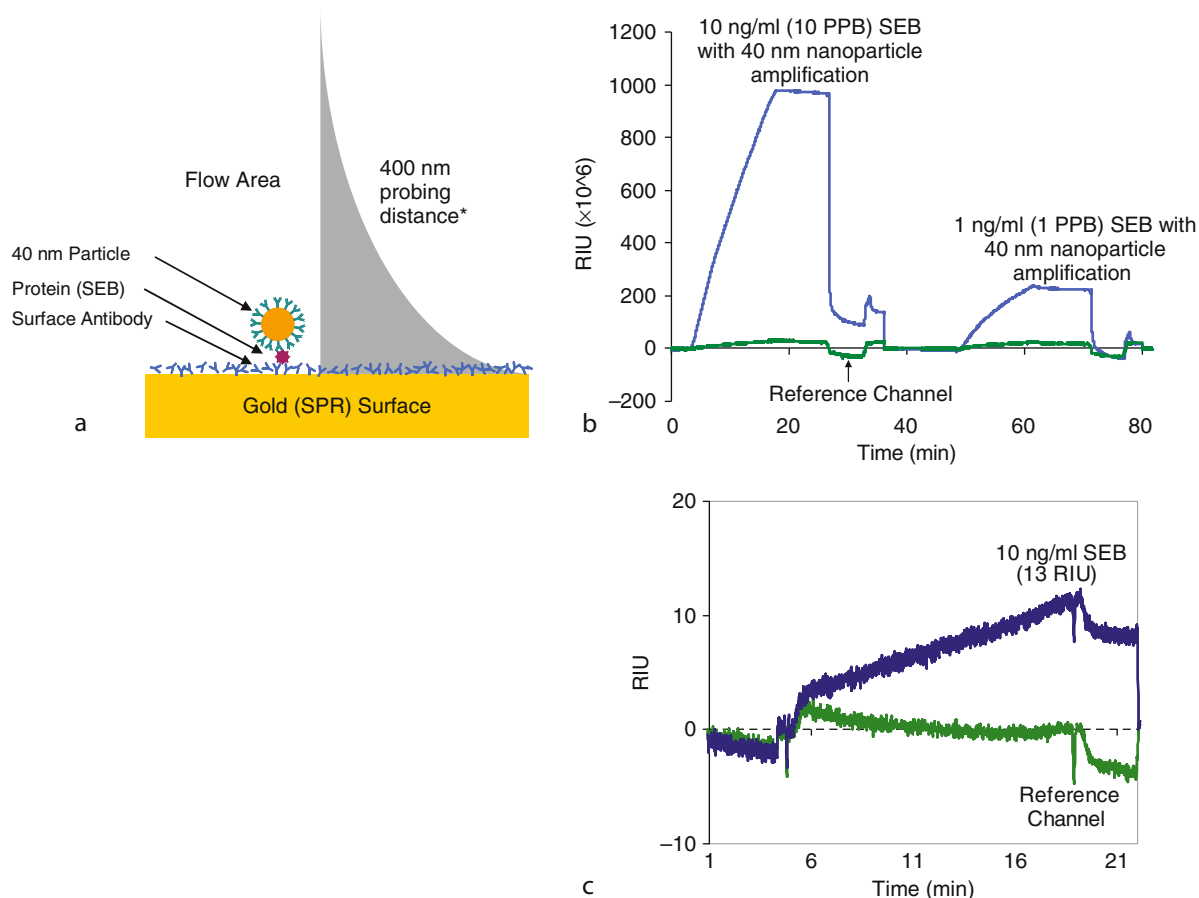
Subtractive Inhibition Assays for Large Molecules (Whole Cells)

To detect large molecules (i.e., whole cells) that lie mostly outside the SPR evanescent wave (Fig. 8) a technique similar to the small molecule competition can be employed. This technique involves addition of antibody to a suspension of bacteria or other larger

particles, and then removal of the antibody-complexed particles by centrifugation or filtration and quantification of the remaining antibodies by binding to anti-antibody RE or immobilized target epitope on the SPR surface. Depletion of antibody signal is proportional to the concentration of analyte in the sample. Simplifying the protocol by eliminating the filtration/centrifugation step and relying on the difference in diffusion rate between the large particles and the antibody can also be employed, although the sensitivity may be affected.

Multiplex Detection

For many environmental biosensing applications it is useful to be able to detect a number of different analytes from a single sample. These include testing for threats from deliberate contamination, from the many potential pathogens in water supplies, testing for different strains of a similar microbial organism, and testing for different chemical pesticides [59] in the field. Figure 14 provides an example of detecting eight different analytes with sequential injections into the same sensor system. The system incorporated eight 3-channel sensors with the same recognition elements on all three channels of each sensor element. This configuration provided binding data in triplicate in real time.



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 13

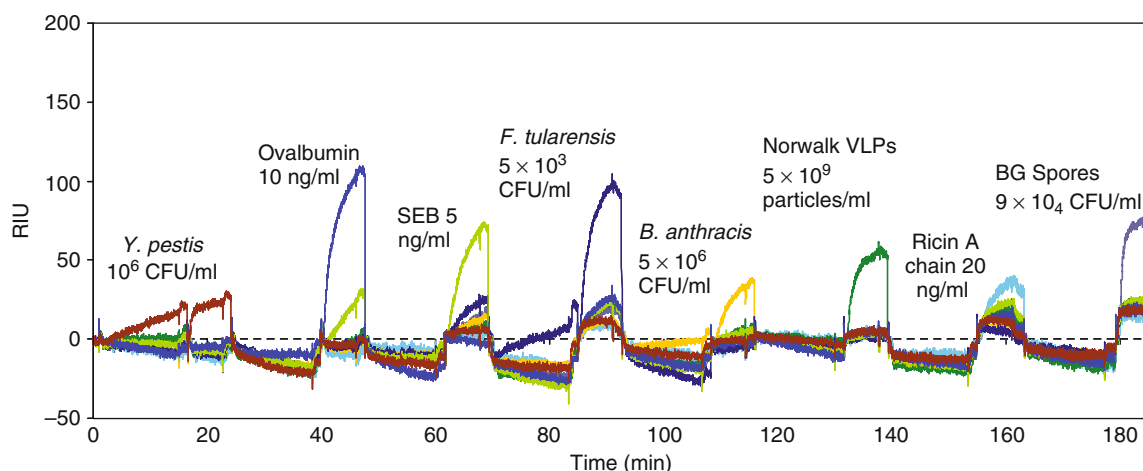
(a) Cartoon of protein (SEB) detection with amplifier in relation to the SPR sensor probing distance. (b) Detection of SEB with amplifier at two different concentrations with a low pH wash to reset the sensor between detection events. Protein (SEB) was mixed with 40 nm particles prior to injection for amplification of the signal. (c) The 10 ng/mL signal without nanoparticle amplification is approximately 13 RIU. Nanoparticle amplification resulted in a 70-fold increase in the SPR signal

Future Directions

The future directions of portable environmental SPR biosensing have been partially defined with the development of the SPR microscope or imager. SPR imagers are a variation of the SPR sensor described here in which light incident at a fixed angle or wavelength illuminates a much larger surface area. The ability of the SPR imaging systems to interrogate multiple different spots or REs on a single chip surface in an array format can also be performed in real time, allowing for hundreds and even thousands of samples to be analyzed simultaneously. A 1,000-spot bench-top array

system has been demonstrated [60], and a prototype portable SPR array imager has also been described [61]. The challenge will be to produce systems that are sufficiently small to be used as portable devices or small, inexpensive bench-top systems. For general laboratory use, the binding partners of interest will include a vast array of different biomolecules, drugs, and other small molecules.

Future enhancements of portable systems will depend on further development of microfluidic and nanofluidic systems, including microvalves and pumps, simplification of the user interface, smaller processors and control electronics, and perhaps the



Biosensors and Bioassays for Ecological Risk Monitoring and Assessment. Figure 14

Serial detection of *Yersinia pestis*, Hen egg ovalbumin, *Staphylococcal* enterotoxin B (SEB), *Francisella tularensis*, *Bacillus anthracis* spores, Norwalk virus-like particles (VLPs), ricin A chain, and *B. subtilis* (BG) spores at the indicated concentrations with single steps of antibody amplification after each direct binding step

further reduction in size of the sensing element. The currently available SPREETA biosensor element is only about one-fourth the size of the original devices. Refractive index is highly sensitive to small temperature changes, and reduction in the size of the temperature control circuitry will allow for further miniaturization of portable sensor systems. Simply reducing the size of the existing portable systems to hand-held devices will provide instruments with a broad range of applications.

The continued development of recombinant antibody selection and expression systems such as recombinant *E. coli* single chain camelid antibodies [62] will be important for generating both wild-type and variant recombinant proteins that will be useful as inexpensive sensor recognition elements. This is an area that can benefit from increased efforts and funding. The reduction in antibody costs will be especially important for protocols that consume reasonable quantities of antibodies, such as those utilizing amplification approaches.

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Biosynthetic Natural Gas

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Article Outline

Glossary

Definition of the Subject

Introduction

Biomass Resources

Biomass Supply

Bio-SNG Conversion Technology

Distribution Infrastructure

Assessment of Bio-SNG Provision Pathways

Future Directions

Bibliography

Glossary

Biomass gasification Thermochemical conversion process, where the gasification media (pretreated solid fuel) is converted into a gaseous fuel (called raw gas).

Bio-SNG Biosynthetic Natural Gas is a gaseous biofuel provided via thermochemical conversion including the steps biomass gasification and subsequent methanation.

Methanation Methanation is a catalyst-based synthesis with the aim to provide methane from a syngas. Therefore, the gas components hydrogen and carbon monoxide occurring within the syngas are converted to methane and water-steam.

Tri-generation Technology for the parallel production of the energy carrier heat, electricity, and fuel (e.g., conversion of biomass into heat, electricity, and Bio-SNG) with varying shares according to the given demand.

Definition of the Subject

Since the discussion on climate protection started and numerous countries declared defined goals for the use of renewable sources of energy in the heat, electricity as well as in the transportation sector, the request to

develop promising and sustainable nonfossil energy pathways gain more and more importance on the political agenda. Under the various renewable sources of energy biomass and especially solid biofuels contribute already significantly within the global energy system mainly due to the easy availability of solid biomass and the ability to cover the given demand anytime (e.g., application for cooking purposes in developing countries, provision of heat in countries with a cold season). Beside these established pathways, new routes for an efficient and sustainable biomass use are under development. One promising example of such a new provision chain is the conversion of solid biofuels via gasification and subsequent methanation into Biosynthetic Natural Gas (Bio-SNG) to be used as a substitute for Natural Gas. This provision pathway allows the use of local available lignocellulosic biomass for the efficient production of a well-known gaseous energy carrier (i.e., Bio-SNG). Thus, this energy carrier can substitute Natural Gas and can help to reduce the energy-related greenhouse gas (GHG) emissions. With the use of Bio-SNG in the mobile and stationary sector, the already existing infrastructure can be used. Based on this, the aim of the following explanations is to present such Bio-SNG provision chains in detail and to assess them concerning technical, economic and environmental aspects.

Introduction

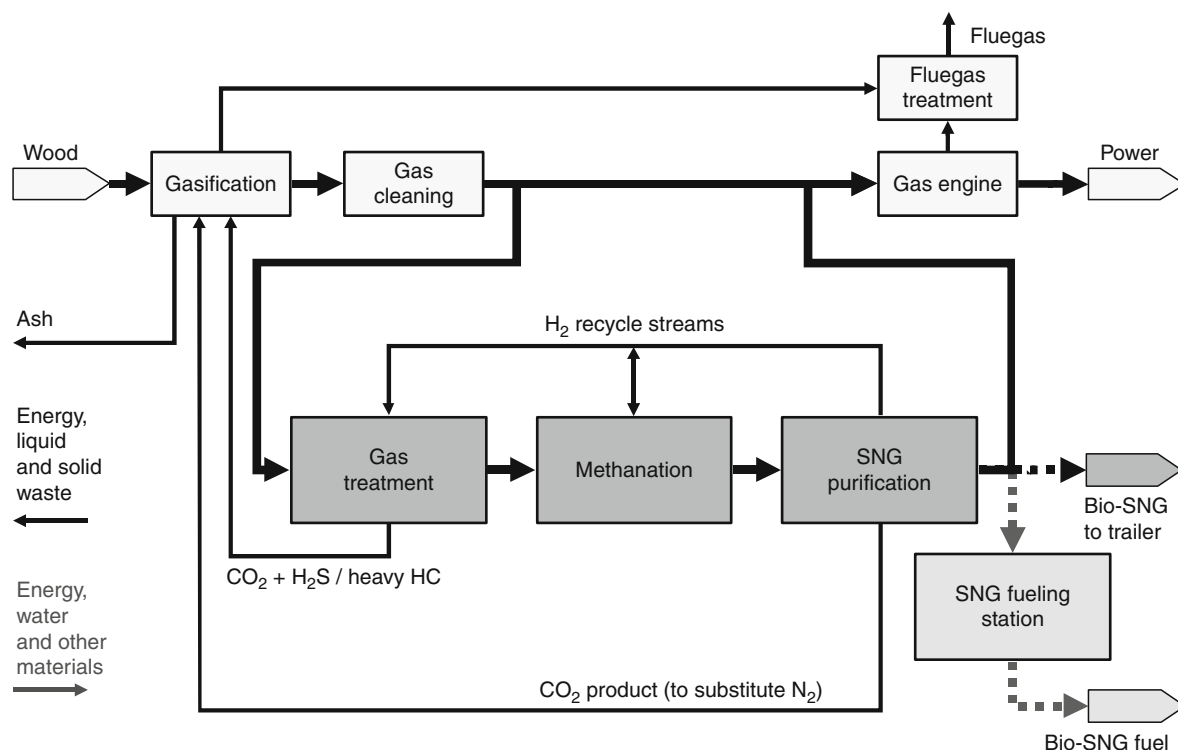
Within the global energy system, Natural Gas is an important energy carrier. Related to the overall primary energy consumption Natural Gas contributes currently with a share of 20.5%. And the demand for Natural Gas is projected to increase until 2030 by more than 50%. For the sectors residential, services, and agriculture as well as industry, an annual growth rate between 1.2% and 1.4% is expected globally. In contrast, the power sector is characterized by a projected growth rate of 2.4% and an overall market share of 45% by 2030 [1]. Additionally, the infrastructure to distribute and store Natural Gas is fully available and has been improved continuously during recent years. Beside a highly efficient energetic utilization for stationary and mobile application, Natural Gas can be used as a raw material, e.g., within the chemical industry [2].

Since numerous countries introduced legislative frame conditions to implement the Kyoto Protocol (e.g., European guideline 2009/28/EG) or to reduce CO₂-emissions (e.g., EU wide CO₂-control for passenger cars and light-duty vehicles), the substitution of fossil energy gains more and more importance. Beside this, selected countries dominate the supply of fossil energy carriers like Natural Gas and create therewith a substantial import dependency. The substitution of Natural Gas through biomethane is therefore an option allowing solving several problems and facing some important challenges at once.

For the production of biomethane, two conversion pathways are market ready respectively under development at the moment [3]. Beside the biogas pathway (i.e., the biochemical biomass conversion), the thermochemical conversion of solid biomass is another promising option to produce biomethane (here called: Biosynthetic Natural Gas or Bio-SNG to avoid a misunderstanding with biomethane from anaerobic processes).

The entire provision chain of Bio-SNG is characterized by some advantages compared to other biomass conversion routes. Relatively, small production systems (starting from a few 10 MW thermal capacity) enable the use of locally available biomass without too long transport distances. The possibility of tri-generation (i.e., the production of heat, power, and fuels) allows high overall efficiencies and therewith a high CO₂ mitigation potential. Due to a more market-ready technology and smaller conversion units, fewer risks are given in comparison to the production of BtL-fuels. Bio-SNG can be distributed and stored with the very well-developed Natural Gas grid that makes it possible to transport the biomethane together with Natural Gas from the source to the end user [4].

The production of Bio-SNG can be carried out via steam gasification of woody biomass, gas cleaning, subsequent methanation, and raw gas upgrading (Fig. 1). The steam gasification and a subsequent gas cleaning have been demonstrated successful in a technical scale of 8 MW thermal capacity at the biomass combined heat and power (CHP) gasification plant in Güssing/Austria since 2002. Steam gasification leads to a producer gas with a relatively high content of hydrogen and methane. These properties are necessary for an efficient SNG production [5].



Biosynthetic Natural Gas. Figure 1
Basic process flow diagram

Biomass Resources

Taking into consideration the technical requirements of the conversion technology (e.g., gasifier requirements), solid biofuels seem to be promising for the production of Bio-SNG from the current point of view. Thus, woody and herbaceous biomass material streams are favorable resources. Based on the CEN classification standard (i.e., European Committee for Standardization), the following solid biofuels are of great importance [6]:

1. Forest and plantation wood
2. Wood processing industry by-products and residues
3. Used wood
4. Herbaceous biomass from agriculture and horticulture
5. Herbaceous processing industry by-products and residues

Based on the gathered experiences in the field of biomass pretreatment and biomass gasification, the qualitative requirements can be defined in accordance to the standard ÖNORM M 7133. Table 1 gives an exemplary overview to qualitative requirements on woody biomass suitable for the production of Bio-SNG [7].

Biomass Supply

The decentralized availability of biomass develops partially complex provision structures as well as numerous capacity-related bottlenecks along the entire biomass supply chain closing the gap between the place of biomass production and use. In this context, it is necessary to integrate efficient provision concepts into the local and regional frame conditions (e.g., biomass potential, infrastructural aspects) in order to achieve a high logistic performance and low provision costs free plant gate as well as low environmental effects.

Biosynthetic Natural Gas. Table 1 Selected specifications for solid biofuels for the Bio-SNG production

Criteria	Unit	Specification
Origin	–	Woody biomass from forest residues and short rotation coppices
Product	–	Wood chips
Water content	In%	20 up to 30
Size	In mm	30 up to 50
Share of impurities	–	Rough impurities (like stones, metal pieces, and other contaminants) as well as the addition of combustible impurities (like abrasive dust) are not permitted
Ash content	In%	<2

Concerning the configuration of biomass supply chains a wide range of approaches are possible. The overall objective of the provision of solid biofuels to Bio-SNG production plants (and in general to biomass conversion plants) is the optimized combination of the preconditions at the source with the requirements of the sink (respectively conversion plant) along the entire supply chain. This includes the adjustment of the qualitative and quantitative fuel requirements as well as further technical, spatial, and time-related criteria.

Beside a high technical biomass potential for a certain fuel assortment aspects like the catchments area, the necessity of a fuel conditioning, transport distances as well as the distribution of storages are of importance for the configuration of the overall supply chain. Depending on the conversion plant size, different transport modes seem favorable and can be divided into the (a) road, (b) rail, and (c) water way transport. The latter can be distinguished into the inland water way and overseas transport. Beside a straight supply of the biomass to the Bio-SNG facility, the provision of the relevant biofuels is also possible through numerous intermediate steps.

The solid biofuel provision to Bio-SNG plants is characterized by fully mechanized concepts. Via road transport, the supply is usually carried out with swap bodies. For the provision of biomass assortments with

intermodal systems, relying on train transport as main mode, the preliminary run (road transport) and the main run is integrating swap bodies as well. To overcome medium distances the use of container systems is promising, since the handling process is more efficient and the down times of the transport media can be reduced. The provision of solid biofuels via inland waterway or overseas is based on the bulk transport. This is true, because the transport is carried out over longer distances and is due to the transport mode more time consuming. Therefore, it is necessary to exploit the load unit by using bulk goods.

Between the different supply approaches significant differences with regard to the logistic efficiency, the complexity of the supply chain as well as the infrastructural flexibility exist. While the logistic efficiency for the road-based supply is the highest, this alternative is limited in terms of transport distances. The intermodal transport is in general characterized through higher complexity and lower logistic efficiency, whereas it is more convenient for the long-distance biomass supply. In the field of infrastructure flexibility, direct supply via road transport is in most cases the most convenient alternative [8].

Bio-SNG Conversion Technology

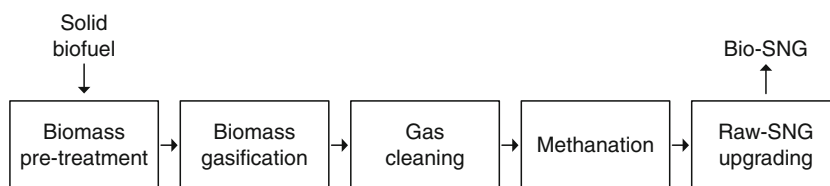
The thermochemical production pathway of synthetic Natural Gas aims to convert solid biofuels into gas with high methane content (approx. 95%). The conversion from solid biomass to Bio-SNG at a certain location can be subdivided into five process steps:

1. Biomass pretreatment
2. Biomass gasification
3. Gas cleaning
4. Methanation
5. Raw-SNG upgrading (Fig. 2)

In the following, the technology of these process steps is described in detail.

Biomass Pretreatment

Due to its inhomogeneous characteristic, solid biofuels have to be pretreated before gasification to ensure a reliable feeding into the gasification reactor on the one hand and to allow for optimal gasification conditions inside the gasification reactor on the other. Thereby, in



Biosynthetic Natural Gas. Figure 2

Scheme of Bio-SNG conversion pathways

general, the pretreatment focuses on an adaption of the biomass size to meet the demands of the feeding system and on the drying of the biomass to reduce the energetic losses within the gasification process [9]. As entrained-flow gasifier requires a pumpable or dispersible fuel, their application demands a special biomass pretreatment (e.g., pyrolysis, torrefaction) [10].

The pretreatment of the solid biofuel necessary for the reasons outlined above can be realized with mechanical, thermal, and thermochemical processes.

Mechanical Pretreatment Mechanical biomass pretreatment processes comprise primarily process steps like size reduction, sieving, and/or pressing of the fuel to ensure a homogeneous particle size and particle form [11] to prevent locking of the gasifier's feeding system and to ensure a uniform flow regime inside the gasification reactor.

Thermal Pretreatment The thermal biomass pretreatment comprises biomass drying in order to increase the biomass' quality and heating value and to reduce its weight [11]. Such drying processes can be distinguished in natural and technical drying. For Bio-SNG production pathways, technical drying processes are – due to the disposability of process heat and the need for low biomass water contents (approximately 10–20%) permitting an energy-efficient gasification process [9] – of particular interest.

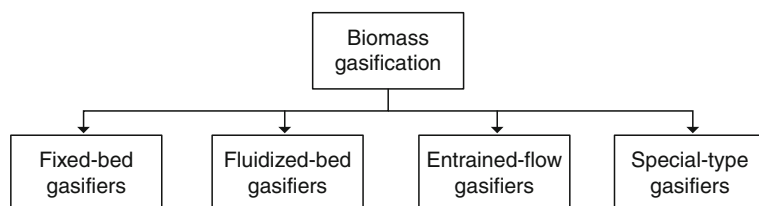
Thermochemical Pretreatment With regard to Bio-SNG production pathways, thermochemical pretreatment methods primarily aim to meet the demands of entrained-flow gasification systems. Regarding the biomass pretreatment to allow for their use in entrained-flow gasification systems, two methods are under discussion: torrefaction [12] and

pyrolysis [13]. Both methods operate under absence of external oxygen. While torrefaction processes deaerate water and volatile components [11, 14], pyrolysis processes decompose the biomass into three products: gas, condensable hydrocarbons (pyrolysis oil after condensation), and char. Thereby, here the flash pyrolysis is of particular interest as this process allows to achieve high pyrolysis oil yields [15]. The use of torrefaction and pyrolysis products in entrained-flow gasifier is still under investigation and cannot be considered as state of the art.

Biomass Gasification

Gasification is a thermochemical conversion process, where the gasification media (pretreated fuel) is converted into a gas (called raw gas) with the main components CO_2 , CO , H_2O , H_2 , and – depending on the gasification parameters – certain amounts of CH_4 . As the process is endothermic, heat has to be supplied. Beside the main gas components mentioned above, the raw gas may contain different impurities like particles, tars, sulfur compounds, nitrogen compounds, halogens, and alkali compounds. The amount of these impurities within the raw gas depends on multiple process conditions and can be influenced to a certain degree by gasification technology and conditions [10, 11, 16, 17].

The available gasification processes can be distinguished according to the (a) gasification agent, (b) gasification pressure level, (c) heat supply, and (d) reactor design. The reactor design is related to different scale potentials and therewith characteristic for the subsequent gas usage. According to the fluid-dynamic behavior of the fuel in the gasifier, the following reactor designs can be used in general for the provision of a raw gas (Fig. 3).



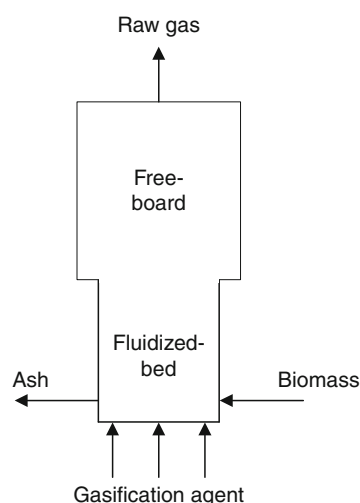
Biosynthetic Natural Gas. Figure 3
Reactor designs of biomass gasification systems

Regarding the Bio-SNG production, in general the following two reactor designs are most important according to current knowledge.

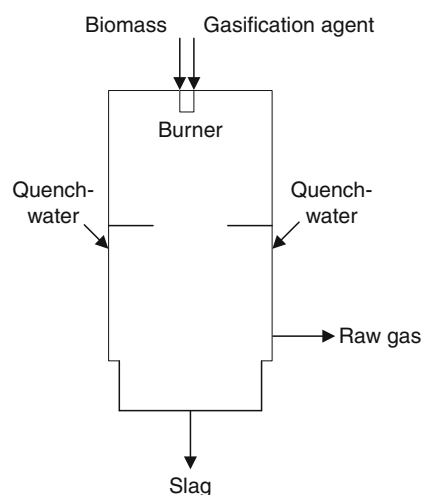
Fluidized-Bed Gasifier Fluidized-bed gasifier (Fig. 4) is characterized by the fluidization of fine-grained inert material (e.g., sand) and solid feedstock particles inside the reactor. Thereby, the mixture of inert material and feedstock particles behaves similar to a fluid. Due to the homogeneous feedstock allocation inside the reactor, there are no separated reaction zones, the temperature level (between 700°C and 950°C) is easily to be adjusted, and the heat and mass transfer within fluidized-bed reactors can be optimized in comparison to fixed-bed gasifier. However, the dust content of the raw gas is relatively high [11, 18]. Fluidized-bed gasifier is distinguished as (a) stationary, (b) circulating, and (c) twin-bed fluidized-bed gasifier.

Entrained-Flow Gasifier Entrained-flow gasifier (Fig. 5) is commonly applied for coal gasification. Here the gasification media consisting of (very) small particles is gasified within seconds at temperatures of 1,300–1,600°C and pressures up to a 60 bars [10]. In general, oxygen is used as a gasification agent. The resulting raw gas is free of tars and has a low methane content - in comparison to the fluidized-bed gasifier where the raw gas is characterized by a high tar and methane content.

The main advantages of entrained-flow gasifier are high carbon conversion rates and a tar-free raw gas. The effort on gasification and handling of the process parameters (high temperatures and pressures) are disadvantages of this design. Entrained-flow gasifier is under discussion for plant sizes of several hundred megawatts [10, 19].



Biosynthetic Natural Gas. Figure 4
Scheme of stationary fluidized-bed gasifier



Biosynthetic Natural Gas. Figure 5
Scheme of entrained-flow gasifier

Gas Cleaning

Depending on the gasification parameters (e.g., reactor design, gasification pressure, gasification temperature, and gasification agent), the raw gas contains different impurities as (Fig. 6) [20]:

- Particles (e.g., char, dust, ash, bed material)
- Tars (e.g., C_7H_8 , $C_{10}H_8$)
- Sulfur compounds (e.g., H_2S , COS, thiophenes)
- Nitrogen compounds (e.g., NH_3 , HCN)
- Halogens (e.g., HCl)
- Alkali compounds (e.g., Na- and K-compounds)

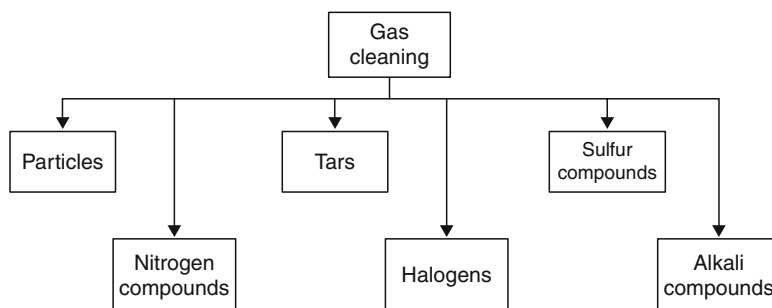
To avoid catalyst poisoning in the subsequent synthesis (e.g., caused by organic sulfur) and damage at other plant components (e.g., corrosion at heat-exchanger surfaces), the raw gas has to be cleaned after leaving the gasifier. To remove the impurities mentioned above, various cleaning methods are available at the market.

Particles Particles can be removed from gas streams by cyclones, filters, electrostatic precipitators, or washing systems. Cyclones are applied for a rough particle removal. They separate particles above 5 μm by centrifugal forces and characterized by robust and simple design and low-pressure drop within the gas. Filters are appropriate for a fine particle separation even of particles below 5 μm . However, a drawback of filters is the pressure drop especially for increased separation rates. Electrostatic precipitators achieve a high particle separation in combination with low-pressure drops. They operate either dry or wet. But they need a high technical effort in comparison to cyclones and filters.

Washing systems (e.g., Venturi washers) are able to remove even smaller particles as well as additional gas impurities. However, the technical effort of washing systems for particle removal is very high as a subsequent separation of withdrawn particles from the solvent is usually necessary [11, 17].

Tars Tars can be removed from the gas by catalytic or thermal tar cracking as well as by washing with organic medium and water. At high temperatures, tars are cracked into small molecules like CO and H_2 . For this process, high temperatures (around 1,200°C) or/and long residence times are necessary. However, the provision of such a high temperature level lowers the process efficiency. Compared to this catalytic tar cracking requires lower temperatures (around 850°C). But so far no cheap catalysts with a long technical lifetime are available on the market. Tar can also be washed out from the gas with water. Thereby, the raw gas is cooled down to condense the tars. But then the contaminated washing water has to be cleaned. Therefore, in recent years washing systems using organic washing media have been developed. The advantage is that the contaminated solvent can be burnt. Therewith, purities of about 10 mg/m^3 (i.N.) can be achieved [11, 17].

Sulfur Compounds Sulfur can be removed by adsorptive and/or absorptive methods. ZnO and active carbon beds are commercially available adsorptive processes for sulfur removal. Both systems have to be regenerated from time to time. To reduce the respective effort and to ensure high sulfur separation rates, active carbon bed and ZnO-bed can be combined: with active carbon beds a rough and with ZnO



Biosynthetic Natural Gas. Figure 6
Categories of raw gas impurities

a fine sulfur removal is achieved. If larger amounts of sulfur have to be removed from the gas, technically complex systems known from coal gas cleaning can be used (e.g., Rectisol washing, Selexol washing, Amine washing) [11, 17].

Nitrogen Compounds, Halogens, and Alkali Compounds

Nitrogen compounds and halogens are separated from the gas by adsorptive and absorptive methods mentioned above. To improve the separation rate, these methods can be adapted to the impurity to be removed (e.g., by the addition of sodium hydroxide to water solvent). A common way to remove alkali compounds from the gas is to condense them (below 600°C) and remove them by conventional filter techniques [11, 17].

Methanation

The process step methanation comprises a catalyst-based synthesis with the aim to increase the methane content of the cleaned gas. Thereby, the gas components hydrogen and carbon monoxide are converted to methane and water vapor (Eq. 1).



In principle, all metals of the eighth main group catalyze the methane synthesis. However, due to their availability and price stability the use of nickel catalyst is of particular interest [21]. This catalyst operates within a wide pressure (1–80 bar) and temperature range (250–650°C), but the desired formation of methane is enhanced at low temperatures and high pressures. To ensure a high carbon monoxide conversion, a H₂/CO-ratio of at least 3/1 is advisable. However, as raw gases from biomass gasification processes are typically characterized by H₂/CO-ratios of 0.3–2.0, in general an adjustment of this ratio is foreseen either by adding additional hydrogen or by converting carbon monoxide and water vapor into hydrogen and carbon dioxide according to the water gas shift reaction (Eq. 2).



As nickel catalysts catalyze the water gas shift reaction as well at elevated temperatures and pressures, the water gas shift reaction can be integrated in the

methanation reactor instead of an upstream shift-reactor before the methanation.

Basically, methanation reactors can be distinguished according to the fluid-dynamic behavior of their catalysts in fixed-bed reactors and fluidized-bed reactors.

Fixed-Bed Reactors Due to the exothermal methanation reaction and limited axial and radial heat transfer rates of fixed-bed reactors, an isothermal operation is only possible with low conversion rates or high technical and operational effort [21]. For a reasonable heat management, multiple fixed-bed reactors with limited conversion and thus limited heat transfer rates are combined with each other in series, parallel or mixed arrangements.

Fluidized-Bed Reactors In contrast to fixed-bed reactors, fluidized-bed reactors are characterized by a fluidized-bed of the catalyst inside the reactor. To realize a quasi-isothermal operation, the reaction heat can be managed with help of an internal heat exchanger. Therefore, even high gas and heat flows can be handled with a single methanation reactor [22, 23].

Raw-SNG Upgrading

To feed Bio-SNG into the Natural Gas grid, it has to fulfil the quality requirements of the grid. Therefore, after the methanation an upgrading of the raw Bio-SNG is necessary. This includes the separation of carbon dioxide, water, and – depending on the raw-SNG quality – other gas components (e.g., hydrogen). Thereby, beside the Bio-SNG composition and purity, the Wobbe index is of particular interest.

For all raw-SNG upgrading steps, several technologies are available at the market and in operation for treatment processes of SNG from coal, Natural Gas treatment processes, and biogas upgrading processes. However, due to their different technical and operational effort, selected technologies are advisable for small-scale applications and others for large-scale applications. In the following, the most important techniques – with regard to Bio-SNG production – for raw-SNG drying and carbon dioxide removal are described.

Carbon Dioxide Removal Considering the carbon dioxide removal, absorptive and adsorptive processes are available.

A relevant adsorption process for Bio-SNG production systems is the pressure swing adsorption (PSA) for the adsorption of carbon dioxide on an active carbon bed [24]. Absorption processes can be realized based on physical and chemical processes. While physical absorption processes only based on the solubility of the absorptive in the solvent, within chemical absorption processes a chemical reaction between solvent and absorptive takes place to separate the gaseous components from a gas flow. Examples for physical absorption process are the Rectisol process [25] and the Selexol process [26].

Drying For the raw-SNG drying, in general, the gas is cooled down below the water dew point. For further drying, adsorptive and absorptive methods can be applied [27].

Distribution Infrastructure

The Natural Gas grid is classified into four different grid levels. The international pipeline system (level 1) for long-distance transport of Natural Gas is operated on a pressure level of 80 up to 120 bars. An average standard gas volume for such a grid is about 1.0 up to 2.5 $\text{mn m}^3_{\text{gas}}/\text{h}$. For the national transport of gas (e.g., within Germany, the Netherlands or Austria), a high-pressure grid for the long-distance transport is available (level 2). Such a pipeline system is usually in operation with a grid pressure of 25 up to 80 bars. The connection between long-distance pipeline networks and local gas grids is realized by a regional pipeline system (level 3). These networks are characterized through a wide bandwidth of the pressure level (from 1 up to 70 bars). With the help of the local gas grid, the Natural Gas is distributed to the final consumer (level 4). The lowest pressure level of such a pipeline system is in the range of 30 up to 100 mbar.

From the technical point of view, the feed-in of upgraded biomethane with a defined gas quality is possible in high-pressure gas grid. For medium- and low-pressure grids are in general the required floats not necessarily sufficiently given [28]. But locally a different situation might be given.

The technologies for the feed-in of biomethane into the Natural Gas grid (e.g., compressors) are market ready and commercially available. For the injection of the biomethane in the pipeline, a lifting of the pressure above the grid pressure is required [28].

Therewith the possibility is given to produce Bio-SNG for instance at a place where the plant site requirements are fulfilled (e.g., biomass availability, favorable infrastructure for the provision of biomass and distribution of the produced energy, and heat sink) and to distribute the biomethane via the existing gas pipeline system to the final consumer. The decoupling of the production and utilization allows the efficient application for the generation of heat and electricity. Beside this, Bio-SNG is a favorable alternative for mobile applications (e.g., passenger cars, light heavy-good vehicles).

Assessment of Bio-SNG Provision Pathways

According to the multitude of available technologies, different Bio-SNG production pathways are currently under discussion. Thereby, aspects like (a) the biomass assortment, (b) the plant capacity, or (c) the biomass conversion and especially the gasification system have major influence on the overall system. Therefore, below selected reference concepts are defined and assessed with regard to technical, economic, and environmental criteria.

Reference Concepts

Here are concepts for the provision of Bio-SNG defined (Table 2). Both pathways can be assigned to different time frames. While the concept “fluidized-bed” is oriented on the short term (2015), the “entrained-flow” concept is an alternative for a medium term (2020–2025). The described capacity, operation hours, etc., create the frame conditions of the investigated system and the base for the assessment of the Bio-SNG provision pathways.

The concept “fluidized-bed” represents the “state-of-the-art” technology based on fluidized-bed gasification. This concept is analyzed for a plant scale of 30 MW. It is assumed that forest wood is used as a raw material.

The “entrained-flow” concept represents a future concept with torrefaction as a biomass pretreatment

Biosynthetic Natural Gas. Table 2 Reference concepts and their frame conditions

Criteria	Unit	Concept “fluidized-bed”	Concept “entrained-flow”
Capacity	MW _{bf}	30	200
Operation hours	h/a	8,000	
Fuel demand	t _{dm}	50,000	350,000
Bio-SNG output	m ³ _{SNG} /h	2,000	13,333
Pressure level gas grid	bar	25	70

step realized at the conversion plant site. This concept is analyzed for a plant scale of several hundred megawatts. Beside wood from forest services, additionally woody biomass from short rotation coppices is foreseen as a biomass feedstock.

The system boundary is defined by the biomass provision step harvest/collection and through the upgrading of Bio-SNG on Natural Gas quality ready for to be feed-in into the gas grid.

For the biomass supply, a full mechanized provision chain is assumed. The storage process is carried out with air tube ventilation systems that allow a reduction of the water content up to 30% (free plant gate). Chipping is performed with truck-mounted chippers at the forest road. For the handling process, discontinuous conveyors are chosen and finally the solid biofuels are transported directly by truck to the Bio-SNG plant. The conversion technology [29] assumed here is based on an atmospheric fluidized-twin-bed biomass gasifier operating with water-steam as gasification agent. Heat for the endothermic gasification reaction is supplied by bed material circulating between the gasification reactor and a combustion chamber [30]. Char and recycled gasification raw gas are used as fuel for the combustion chamber. Tars are removed from the raw gas by a wet washing system using biodiesel as solvent. A fraction of the tar-loaded biodiesel is pumped into the combustion chamber and used as fuel. The methanation is realized within a fluidized-bed methanation reactor [23] and consists of an active carbon and a ZnO-bed.

Afterward the raw-SNG is dried, carbon dioxide is separated from the gas with the help of an amine washing, and hydrogen is removed by membrane technique. The overall system is shown in Fig. 7.

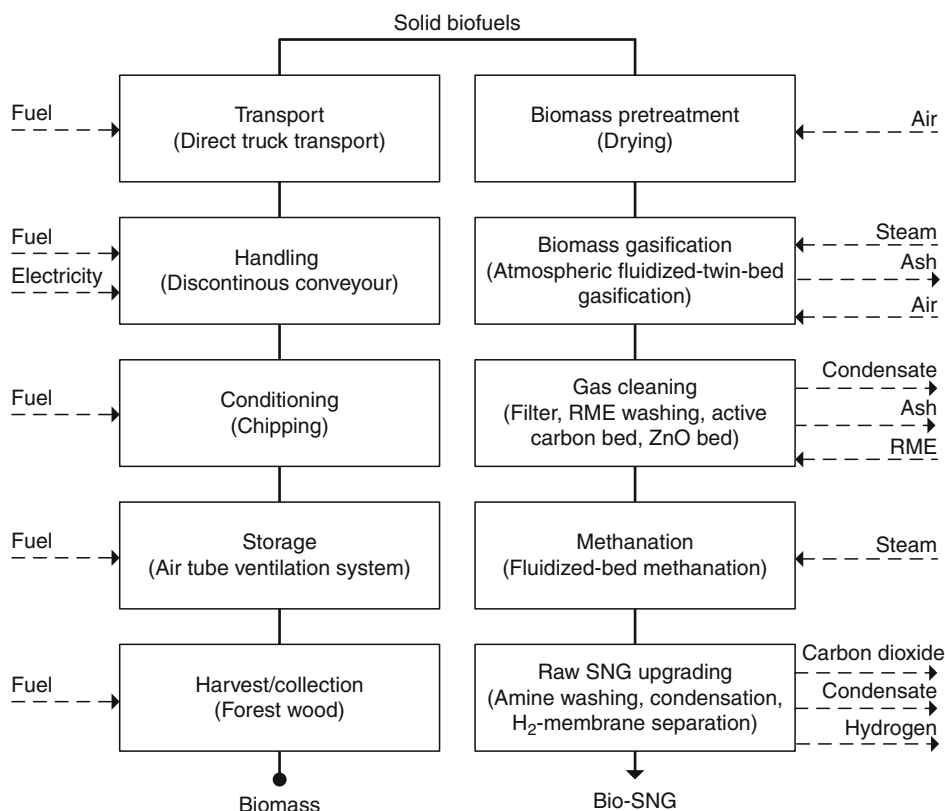
For the reference concept “entrained-flow,” forest and short rotation wood is harvested and collected fully mechanized. At the field or forest, the biomass is stored and chipped for the following transport. The handling from the storage or chipping place into the freight hold of a truck is done with discontinuous conveyor. With the preliminary run, the distance between biomass site and the handling site for the subsequent main run is bridged. With the railway-based transport the main run to the conversion plant is carried out, whereas for the loading process, continuous conveyors are selected. The biomass is provided at the conversion plant with this reference pathway. Here the biomass is torrefied at 250°C before gasification with oxygen as gasification agent [12] takes place. After water quench, the raw gas is cleaned from particles by a Venturi-washing system, conditioned with regard to the H₂/CO-ratio in a water gas-shift reactor and separated from sulfur compounds and carbon dioxide with help of a Rectisol washing. The methanation is realized in an arrangement of fixed-bed methanation reactors. Thereby, additional steam is used to avoid carbon deposition at the catalyst surface. Finally, the raw-SNG is dried by cooling the gas down [27]. The reference concept “entrained-flow” is shown in Fig. 8.

Technical Assessment

In the following, both Bio-SNG production pathways are analyzed and compared from a technical point of view. The technical analysis focuses on the process efficiency of the Bio-SNG provision pathways at plant gate.

The methodological basis for the technical assessment is the calculation of mass and energy balances with a flow sheet simulation. Based on these calculations, the energetic gross and net efficiencies are determined representatively for the technical competitiveness of the process. The efficiencies are defined according to Eqs. 3 and 4.

$$\eta_{\text{gross}} = \frac{|P_{\text{SNG}}|}{|P_{\text{Biomass}}|} \quad (3)$$



Biosynthetic Natural Gas. Figure 7

Schematic overview of Bio-SNG reference concept "fluidized-bed"

$$\eta_{\text{net}} = \frac{|P_{\text{SNG}}|}{|P_{\text{Biomass}}| + |P_{\text{Electricity consumption}}|} \quad (4)$$

According to different frame conditions and assumptions concerning plant site and process modelling, for each process different efficiencies are calculated. Typical ranges of these values of gross and net efficiency are shown in Fig. 9.

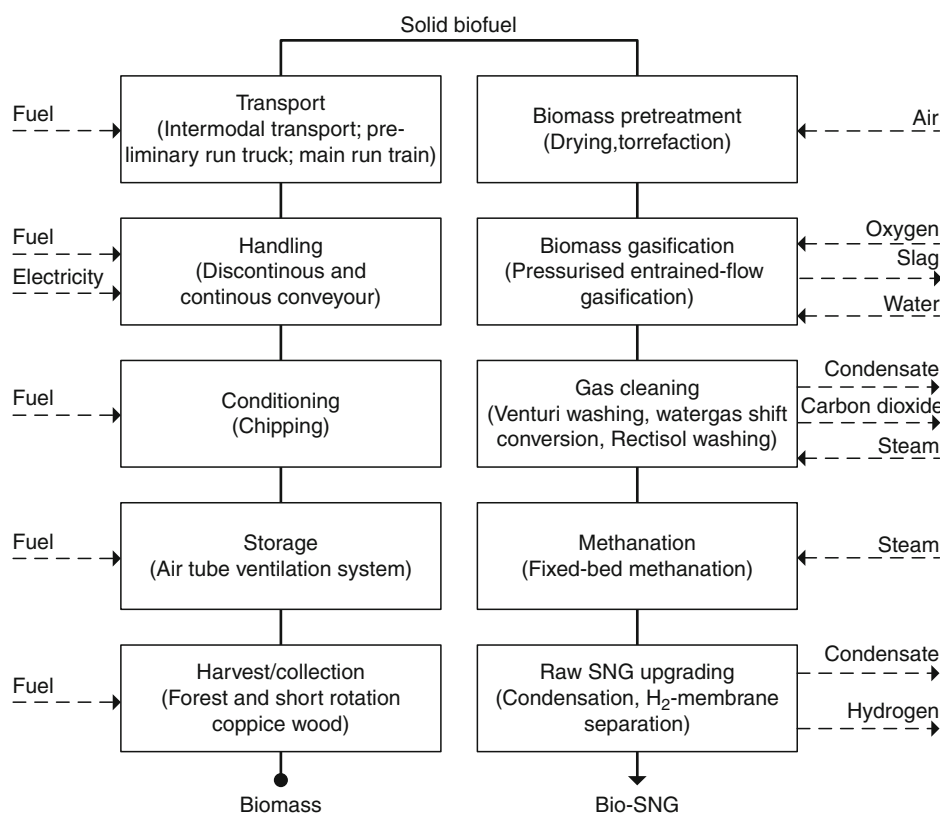
Regarding the results shown in Fig. 9, both Bio-SNG production chains are characterized by net efficiencies in a similar range between 58% and 65%. However, due to process units with a high electrical power demand (e.g., air separation unit, biomass pretreatment), the reference concept "entrained-flow" shows a lower net efficiency than the reference concept "fluidized-bed."

Considering the calculated process efficiency, the overall Bio-SNG conversion chain is characterized by a high biomass-to-SNG rate. Even by including the

plant's electricity consumption, net efficiencies of more than 58% can be achieved. Major losses occur within the process step "biomass gasification" (cold gas efficiency of about 70–80%) and the process step methanation (cold gas efficiency of about 80–90%).

Economic Assessment

For a successful market implementation of Bio-SNG (for instance as a transportation fuel), the production costs are an important indicator. Therefore, the specific Bio-SNG production costs are calculated here based on the annuity method [31]. The annual costs for capital, raw material, and auxiliaries will be allocated with the annual credits for by-products (e.g., heat). Depending on the yearly produced Bio-SNG the specific Bio-SNG production costs can be calculated. They refer to the lower heating value. An overview to the bandwidth of these costs from the regarded concepts is given in Fig. 10.



Biosynthetic Natural Gas. Figure 8

Schematic overview of Bio-SNG reference concept “entrained-flow”

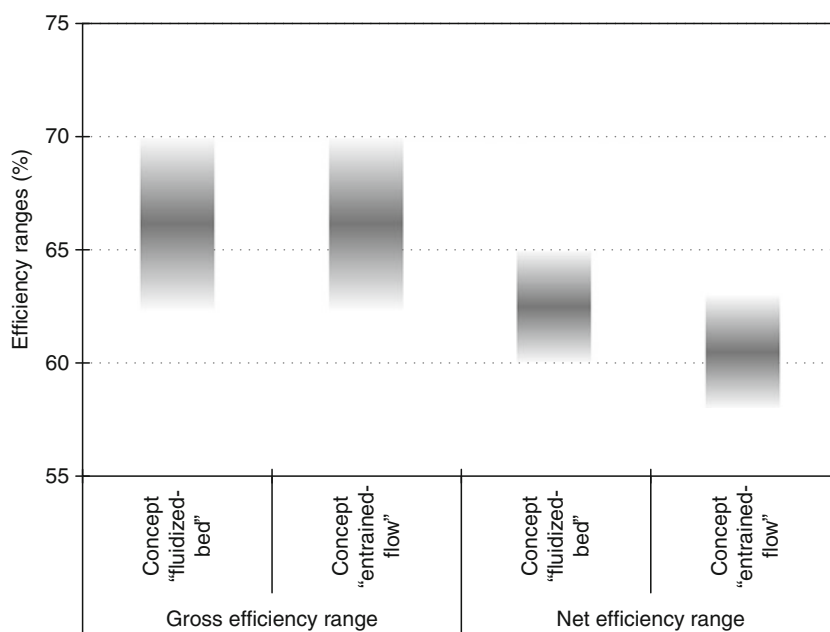
The calculations show Bio-SNG production costs between 0.07 and 0.12 €/kWh_{Bio-SNG}. However, a cost reduction potential is given due to improvement and upscale of the plant concepts. Plants with the “entrained-flow” concept allow a lowering of the specific production costs about 0.01 €/kWh_{Bio-SNG}, mainly due to the economy of scale effect. This is true due to beneficial effects related to the higher capacities (e.g., lower specific costs for investment, maintenance, insurance).

Environmental Assessment

For the environmental evaluation of the defined reference concepts, the specific greenhouse gas (GHG) emissions are calculated in accordance to the allocation method described in the RES Directive [32].

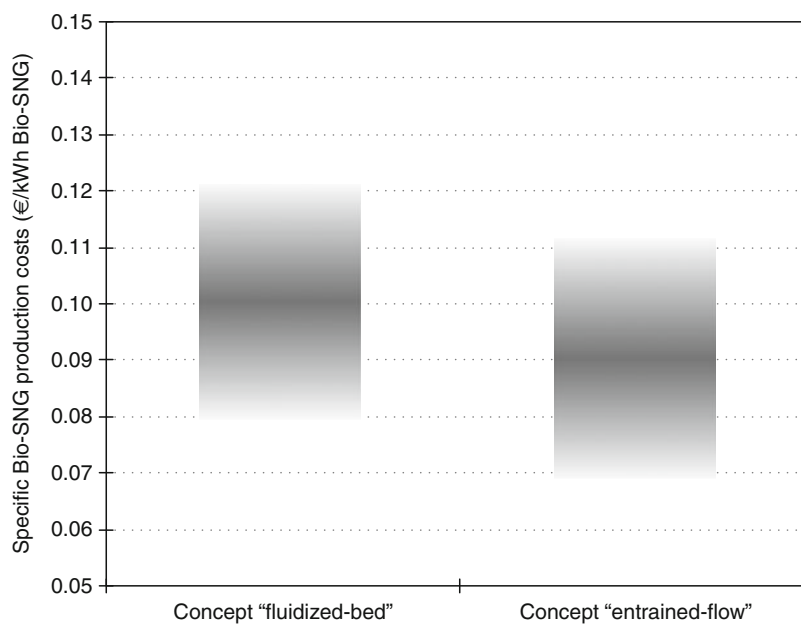
For all steps of the Bio-SNG provision, the relevant inputs of energy or auxiliaries are assessed. The greenhouse gas (GHG) emissions allocated to the products Bio-SNG and heat according to the lower heating values. Greenhouse gas emissions for electricity consumption have been calculated based on the European electricity mix. The results are referred to the defined functional unit 1 GJ_{Bio-SNG}. The results of the regarded concepts “fluidized-bed” and “entrained-flow” are shown in Fig. 11.

For the regarded Bio-SNG provision concepts, specific greenhouse gas emissions between 20 and 35 kg CO₂/GJ_{Bio-SNG} have been determined. The results show that the concept “fluidized-bed” has with 25 kg_{CO2}/GJ_{Bio-SNG} significant lower emissions. In comparison, the concept with entrained-flow gasification is



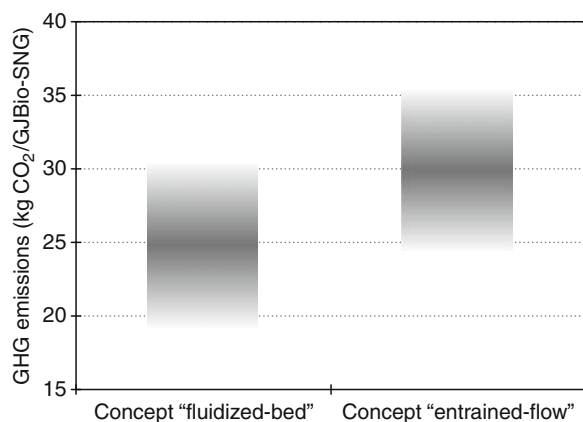
Biosynthetic Natural Gas. Figure 9

Gross and net efficiency range for regarded reference concepts



Biosynthetic Natural Gas. Figure 10

Specific Bio-SNG production costs for the regarded reference concepts



Biosynthetic Natural Gas. Figure 11

Bio-SNG GHG emission for the regarded reference concepts

characterized by about 5 kgCO₂/GJ_{Bio-SNG} higher emissions. This is due to a more complex biomass supply (e.g., longer transport distances, higher number of handling processes), additional efforts within the conversion process (e.g., air separation unit) as well as a lower net efficiency of the conversion.

Overall Assessment

Below, the results of the technical, economic, and environmental evaluations are comprehensively discussed. Beside this, the possible implementation of the relevant Bio-SNG plant concepts will be analyzed with regard to the aspect flexibility.

Both production pathways are characterized by similar gross energetic efficiency, while the concept "fluidized-bed" shows a higher net efficiency. Additional, this production concept is advantageous in terms of environmental aspects. This is mainly due to a less complex supply structure for biomass and shorter transport distances than for concepts with several hundred megawatts fuel input, like for the "entrained-flow" concept. In contrast, the latter concept is beneficial regarding the Bio-SNG production costs (primarily due to the economy of scale effect). Furthermore, it has to be taken into account that with an increase of the scale from the conversion plant a raise of the economic risk in terms of investment costs is given.

For the establishment of a Bio-SNG plant beside infrastructural aspects (e.g., biomass provision – access to traffic infrastructure; distribution of energy carrier – access to gas grid, heat sink) also biomass-related criteria are of importance. Between plants with varying scales, significant differences in terms of site requirements exist. For conversion plants with approximately 30 MW (e.g., concept "fluidized-bed"), the regional availability of biomass is important and a connection to the road network for the biomass supply is sufficient. Compared to this, large-scale concepts need favorable logistic conditions (e.g., access to railway and inland waterway or oversea), while the regional biomass availability is of minor importance. Due to these frame conditions, the site flexibility of Bio-SNG plants with smaller scale is significantly higher.

Summing up, the implementation of Bio-SNG plants with a regional biomass supply seems to be favorable from the technical, environmental, and location-related point of view with plant concepts in the smaller scale (e.g., "fluidized-bed" concept). Only at outstanding sites, an establishment of large-scale production facilities for Bio-SNG is justified.

Future Directions

The demand for Natural Gas is increasing for mobile and stationary application. Due to climate protection reasons (e.g., to reduce greenhouse gas emissions) as well as for energy related reasons (e.g., to diversify supply sources) the substitution of Natural Gas through biomethane is a favorable alternative.

With the production of Bio-SNG, a technically efficient solution is available to provide biomethane in an efficient way in the medium term in significant dimensions. The specific production costs as well as the resulting greenhouse gas emissions depend strongly on the local conditions of a potential conversion plant site and the structure of the biomass provision. However, they are relatively low.

Through a systematic technical enhancement of the entire process chain, the specific Bio-SNG production costs can be reduced and the greenhouse gas mitigation potential can be improved even further.

For a successful market implementation of Bio-SNG, further research and development steps are required. In parallel, the consumer interest has to be raised for this sustainable and alternative biofuel.

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Biotechnology and Nutritional Improvement of Crops

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Article Outline

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Glossary

Antinutrients Substances that interfere with the absorption of nutrients.

Bioavailability The amount of a nutrient in food that can be absorbed and utilized.

Biofortification Any fortification strategy that improves nutritional content at source (before harvest).

Conventional breeding Any process used to create new plant varieties without recombinant DNA technology (e.g., introgression, mutagenesis, and hybridization).

Gene silencing Prevention of gene expression, usually through epigenetic means such as antisense RNA, RNA interference, or de novo DNA methylation.

Genotype The total genetic constitution of an organism.

Inbred Progeny produced as a result of breeding between genetically similar parents.

Introgression The introduction of a new allele from one species into the gene pool of another by repeated backcrossing of an interspecific hybrid with one of its parents.

Locus The position of a gene or other genetic marker on a chromosome.

Macronutrient A nutrient required at levels exceeding 100 mg/day (includes carbohydrates, fats, proteins, water, and fiber as well as certain minerals).

Malnutrition The situation resulting from a nutrient imbalance in the diet, usually referring to a lack of one or more nutrients but equally applicable to nutrient excess.

Micronutrient A nutrient required in minute amounts (typically less than 10 mg/day); includes vitamins and many minerals.

Mineral An inorganic nutrient, usually represented by a soluble ion.

Phenotype The sum of observable characteristics of an organism.

Phytate (phytic acid) A phosphorus-containing compound in the outer husks of cereal grains that, in addition to limiting the bioavailability of phosphorus itself, binds to other minerals and inhibits their absorption.

Promoter The DNA sequence upstream of a gene that regulates transcription.

Quality protein maize (QPM) A variety of maize (corn) developed by CIMMYT that contains 70–100% higher levels of lysine and tryptophan in the grain compared to normal varieties.

Transgene A gene from one species that has been incorporated into the genome of another organism using recombinant DNA technology.

Transgenic plant A plant that carries integrated exogenous DNA in the nuclear genome.

Vitamin An organic micronutrient.

Definition of the Subject and Its Importance

Food insecurity is one of the most important social issues faced today, with nearly one billion people enduring chronic hunger and an additional two billion people suffering from nutrient deficiencies, mostly in

the developing world. Strategies to address food insecurity must ultimately address underlying problems such as poverty and poor governance/infrastructure, but the improvement of agricultural productivity in the developing world is an important goal, and biotechnology is one of a raft of measures being considered to achieve it. Genetically engineered plants provide one route to sustainable higher yields, which will increase the quantity of food available. However, genetic engineering can also increase the nutritional quality of crops, and this is the definition elaborated in this article. In particular, the focus is on biotechnology-based methods to increase the availability of essential nutrients, which are often limiting in human diets and lead to specific deficiency diseases.

Introduction

Food security is taken for granted in the industrialized world, where stable political and social structures ensure that everyone has access to enough safe and nutritious food. In contrast, almost one billion people are chronically undernourished in the developing world, regularly consuming less than 2,000 calories per day [1]. There are also a further two billion people who, despite having access to an adequate source of calories, nevertheless lack essential nutrients; perhaps surprisingly, a significant number of these people are citizens of industrialized countries. This means that up to half the world's population at any one time may suffer from malnutrition [1].

The underlying causes of food insecurity in the developing world are complex but poverty is one of the main factors, reflecting the fact that more than one billion people live on less than US \$1 per day and another two billion are only marginally better off. The world's poorest people tend to be rural farmers in developing countries, depending entirely on subsistence agriculture, whereas less than 1% of the population in the industrialized world are farmers and they tend to farm for profit. Because of limited purchasing power, the poorest farmers cannot irrigate their crops or buy fertilizers, herbicides, and pesticides. This leads to soil exhaustion, falling yields and quality, and the crops become susceptible to pests, diseases, and natural disasters such as drought. In the industrialized world, malnutrition can reflect poverty on the fringes of

society, but is also an educational/lifestyle issue that needs to be approached differently [1].

Any long-term strategy to address food insecurity in the developing world must tackle the underlying problem of poverty by providing rural employment-based income through increased agricultural productivity. Given projected increases in the world's population, the higher cost of oil, falling reserves of fresh water, and greater urbanization, it will certainly be necessary to increase the quality, quantity, and diversity of major food crops. A variety of strategies have been proposed, including the efficient use of organic and inorganic fertilizers, irrigation strategies, soil and water conservation, pest and disease management, and the production of improved plant varieties with higher yields or novel products. Biotechnology provides a range of tools that can be used to improve agriculture in the developing world by lifting yields or increasing food quality, and the latter aspect of biotechnology is considered in this article – the use of biotechnology for nutritional improvement [2, 3].

Overview of Essential Nutrition in Humans

Nutrients and Their Roles in Human Health

Nutrients are chemical substances in food that are necessary for humans to have healthy and active lives. Humans require at least 49 defined nutrients to meet their metabolic needs (Table 1), some highly specific and some represented by families of related molecules. Inadequate consumption of even one of these nutrients will result in adverse metabolic effects leading to poor health, impaired development in children, and (if this is a population-wide problem) an economic impact on society. Table 2 lists the daily guideline amounts in adults for some of these nutrients, as reported by the Food and Agricultural Organization (FAO) of the United Nations and the World Health Organization (WHO) [4]. Table 3 shows some common dietary sources of different nutrients. Generally, nutrients are divided into two broad categories: macronutrients (needed in gram or hundred milligram quantities per day, mainly for energy, structural components of body tissues, and bulk composition of body fluids) and micronutrients (needed in microgram or milligram quantities per day, for many diverse functions).

Biotechnology and Nutritional Improvement of Crops. Table 1 The 49 nutrients essential for sustaining human life [37]

Water and energy	Protein (amino acids)	Lipids-fat (fatty acids)	Macro-elements	Micro-elements	Vitamins
Water	Isoleucine	Linoleic acid	Na	Fe	A
Carbohydrates	Leucine	α -Linolenic acid	K	Zn	D
	Lysine		Ca	Cu	E
	Methionine		Mg	Mn	K
	Phenylalanine		S	I	C (ascorbic acid)
	Threonine		P	F	B1 (thiamine)
	Tryptophan		Cl	B	B2 (riboflavin)
	Valine			Se	B3 (Niacin)
				Mo	B5 (pantothenic acid)
				Ni	B6
				Cr	B9 (folate)
				V	Biotin
				Si	B12 (cobalamin)
				As	Choline
				Sn	
				Co	

Source: [37]

Macronutrients include carbohydrates, fats, proteins, certain mineral ions, water, and fiber, whereas micronutrients include a range of inorganic ions (minerals) and organic molecules (vitamins) [4].

Macronutrients

Carbohydrates and fats consist only of carbon, hydrogen, and oxygen. They are primarily used to derive energy, although they also contribute to some structures in the body, such as the carbohydrates heparan sulfate, chondroitin sulfate, and hyaluronic acid in the extracellular matrix, and various lipid components of cell membranes. Carbohydrates range from simple monosaccharides (e.g., glucose, fructose, and galactose) to complex polysaccharides (e.g., starch, glycogen, the matrix carbohydrates listed above, and cellulose, the predominant component of plant cell walls). All polysaccharides are polymers of monosaccharide units. Therefore, carbohydrates that can be digested by humans are broken down into

monosaccharides and metabolized for energy, used as substrates to synthesize other molecules, or reassembled into energy-storing or structural polymers. Many carbohydrates cannot be broken down in the human digestive system because the corresponding enzymes are not present (e.g., cellulose, inulin) and these are collectively known as dietary fiber. Insoluble fibers such as cellulose help the digestive system function properly (preventing constipation and diarrhea), but there are also many soluble forms of fiber such as inulin which have positive roles in digestion, slowing the movement of food through the gut and facilitating nutrient absorption. Both insoluble and soluble fibers are thought to help prevent colon cancer and cardiovascular disease. Although carbohydrates as a general class of compounds are essential nutrients, no specific carbohydrate is essential because the human body can synthesize all the carbohydrates it needs from simple sugars.

In contrast, fats in the diet include both essential and nonessential molecules. The majority of dietary fat

Biotechnology and Nutritional Improvement of Crops. Table 2 Recommended nutrient intakes for males and females between the ages of 25 and 50 years [37]

Nutrient	Assessment	Male	Female
Energy (kcal)	AEA ^a	2,900	2,200
Protein (g)	AEA	63	50
Vitamin A (mg retinol equivalent)	RDA ^b	1,000	800
Vitamin D (mg)	RDA	5	5
Vitamin E (mg α -tocopherol equivalent)	RDA	10	8
Vitamin K (mg)	RDA	80	65
Riboflavin (mg)	RDA	1.7	1.3
Niacin (mg niacin equivalent)	RDA	19	15
Thiamine (mg)	RDA	1.5	1.1
Pantothenic acid (mg day ⁻¹)	ESADDI ^c	4–7	4–7
Vitamin B6 (mg)	RDA	2	1.6
Vitamin B12 (mg)	RDA	2	2
Biotin (mg day ⁻¹)	ESADDI	30–100	30–100
Folate (mg)	RDA	200	180
Vitamin C (mg)	RDA	90	60
Ca (mg)	RDA	800	800
P (mg)	RDA	800	800
Mg (mg)	RDA	350	280
Na (mg)	MR ^d	500	500
K (mg)	MR	2,000	2,000
Cl (mg)	MR	750	750
Fe (mg)	RDA	10	15
Zn (mg)	RDA	15	12
Cu (mg)	ESADDIC	1.5–3	1.5–3
Se (mg)	RDA	70	55
I (mg)	RDA	150	150
Mn (mg)	ESADDI	2 \pm 5	2 \pm 5
Mo (mg)	ESADDI	75 \pm 250	75 \pm 250
Cr (mg)	ESADDI	50 \pm 200	50 \pm 200
F (mg)	ESADDI	1.5 \pm 4	1.5 \pm 4

Source: [37]

^aAEA, average energy allowance

^bRDA, recommended dietary allowances

^cESADDI, estimated safe and adequate daily dietary intakes

^dMR, minimum requirement

Biotechnology and Nutritional Improvement of Crops. Table 3 Sources of some essential nutrients [4, 5]

Component	Examples of sources
Carbohydrates	Cereal grains and potato
Insoluble fiber	Whole grain barley and vegetable peels
Soluble fiber	Fruits, vegetables, and legumes
Essential fatty acids	Fish, flax seed oils, soybeans, pumpkin seeds, sunflower seeds, walnuts, most vegetables, nuts, seeds, and marine oils
Dietary protein	Tofu and other soy-products, eggs, grains, legumes, and dairy products such as milk and cheese, meat, fish
Vitamin A	Carrots, yams, pumpkins, yellow or orange fruits, fish, eggs, and tuna
Vitamin B1	Whole grains, rice bran, lean meats, legumes, wheat germ, oranges, poultry, fish, and enriched pastas
Vitamin B2	Fortified grains and cereals, leafy green vegetables, poultry, fish, yogurt, milk, and cheese
Vitamin B3	Fortified breads and cereals, brewer's yeast, broccoli, carrots, cheese, dandelion greens, eggs, fish, milk, peanuts, potatoes, tomatoes, tuna, beef liver, and chicken breast
Vitamin B6	Whole grain breads and cereals, fish, chicken, and bananas
Vitamin B9	Pinto beans, navy beans, green leafy vegetables, beef, brown rice, bran, cheese, lamb, liver, milk, mushrooms, oranges, pork, and tuna
Vitamin B12	Ham, clams, cooked oysters, king crab, herring, salmon, tuna, lean beef, liver, and low fat dairy products
Vitamin C	Citrus fruits, strawberries, broccoli, melons, peppers, collards, dandelion greens, onions, radishes, and watercress
Vitamin D	Sun exposure, sardines, salmon, fortified milk, fortified cereals, herring, liver, tuna, margarine, and cod liver oil
Vitamin E	Whole grains, wheat germ, nuts, spinach, and sunflower seeds
Vitamin K	Dark-green leafy vegetables and the skins of fruit and vegetables
Calcium	Dairy products and green leafy vegetables
Magnesium	Fish, dairy products, nuts, soybeans, and cocoa
Phosphorus	Milk, cheese, meats, fish, and eggs
Sulfur	Meats, fish, dairy products, eggs, and garlic
Potassium	Legumes, whole grains, and bananas
Sodium	Table salt (sodium chloride, the main source), milk, and spinach
Chlorine	Table salt and unprocessed foods
Iron	Red meat, and leafy vegetables (especially spinach)
Zinc	Wheat germ, pine nuts, sesame seeds, sunflower seeds, and beefsteak
Manganese	Avocados, berries, nuts, egg yolks, whole grains, green leafy vegetables, and legumes
Iodine	Seafood, dairy products, and iodized salt (table salt)
Fluorine	Drinking water, seafood, teas, and toothpaste
Selenium	Nuts, lamb's kidney, mushrooms, and sunflower seeds
Molybdenum	Legumes, dark green leafy vegetables, and grains
Nickel	Chocolate, nuts, fruits, and vegetables
Chromium	Whole grain breads, brown rice, cheese, and lean meats

Biotechnology and Nutritional Improvement of Crops. Table 3 (Continued)

Component	Examples of sources
Vanadium	Seafood, mushrooms, olives, whole grain breads, carrots, and vegetable oils
Cobalt	Vitamin B12, red meat, fish, eggs, cheese, and milk
Silicon	Whole grain breads and cereals, beets, bell peppers, and legumes
Copper	Beans, almonds, broccoli, garlic, soybeans, peas, and seafood

Source: Revised and updated from [4, 5]

is in the form of triacylglycerides (fatty acid esters of glycerol) and the fatty acids can be interconverted or converted into more specialized phospholipids and sphingolipids that have numerous roles in the body, such as cell membrane components and signaling molecules. Other lipids are derived from cholesterol, which is synthesized in the liver. There are several essential fatty acids as well as fat-soluble vitamins that the body cannot synthesize *de novo*, and these are discussed in detail below.

Proteins are the third major class of macronutrients and these contain nitrogen in addition to carbon, oxygen, and hydrogen. Many proteins also contain sulfur (see below). Fibrous proteins form the structural and mechanical components of tissues (e.g., muscles owe their contractile ability to the proteins actin and myosin, hair and nails are comprised predominantly of keratin, and skin contains large amounts of collagen and elastin). In contrast, most globular proteins are enzymes, the biological catalysts that ensure chemical reactions can take place at the body's ambient temperature. Other proteins fulfill a range of biological functions – signaling molecules and receptors, transmembrane conduits such as ion channels, components of the immune system, effectors of blood clotting, transport and storage of other molecules (e.g., hemoglobin, oxygen, ferritin, and iron), and the control of gene expression. Proteins are linear polypeptides derived from a panel of 20 “standard” amino acids specified by the genetic code (as well as two specialized variants encoded through unique mechanisms), plus a range of posttranslational forms that are generated by chemical modification after protein synthesis. Many of the standard amino acids can be synthesized *de novo* by humans but some cannot, and these are known as essential amino acids (see below). Proteins are described as “complete” in the sense of nutritional

completeness if they provide a source of all the essential amino acids but this designation refers to the sum of all proteins in a meal, not an individual protein molecule.

Essential Amino Acids

Of the 20 standard amino acids, eight (isoleucine, leucine, lysine, methionine, phenylalanine, threonine, tryptophan, and valine) (Table 1) are described as essential because the human body cannot synthesize sufficient amounts *de novo* so they must be obtained from food [5]. A diet that contains adequate amounts of essential amino acids is particularly important during pregnancy, lactation, early development, and following injury. Most plants are deficient in at least one essential amino acid but a balanced diet provides adequate quantities of all. For example, cereal storage proteins are generally deficient in lysine and threonine whereas legumes lack the sulfur-containing amino acids methionine and cysteine. A diet solely comprising one of these protein sources will therefore be deficient for one or more essential amino acids, but it is possible to combine two incomplete protein sources (e.g., rice and beans) to make a complete protein meal, and such characteristic combinations are the basis of distinct cultural cooking traditions. Food from animals, such as meat, eggs, fish, milk, and cheese, provide all the essential amino acids.

Essential Fatty Acids

Fats are more correctly described as triglycerides (three fatty acids attached to one glycerol backbone), and most fatty acids are nonessential in that the body can synthesize them by interconverting other fatty acids. The exceptions are the omega-3 and omega-6 polyunsaturated fatty acids (PUFAs), so named because the first double-bond is found at the third (or sixth) carbon from the terminal CH₃ group. These cannot be synthesized *de novo* from saturated fats, nor interconverted,

and must be obtained from the diet [6]. There are several essential fatty acids in each category, but the body can synthesize any omega-3 fatty acid given a source of one of them (ditto for the omega-6 fatty acids) and therefore only the group is defined as essential. The simplest source of omega-3 is α -linolenic acid and the simplest source of omega-6 is linoleic acid. Good sources of both these molecules include fish, shellfish, seeds, nuts, and leafy vegetables.

Macrominerals

Minerals are inorganic molecules, and those required at levels exceeding 100–200 mg/day (calcium, chlorine, magnesium, phosphorus, potassium, sodium, and sulfur; see Table 2) are known as macrominerals [4]. Their function is generally structural and/or electrolytic/osmotic, although they may also perform additional specialized roles. For example, calcium is an important electrolyte in muscles and in the digestive system, but is also a structural component of bones and teeth, and furthermore acts as a signaling molecule and as a trigger for the transmission of nerve impulses. Sodium, potassium, and chlorine are key electrolytes that maintain osmotic balance in cells. Magnesium is an important buffer and stabilizer for organic phosphates including nucleic acids, and is absolutely required for the activity of adenosine triphosphate (ATP). It is also part of the active site of many enzymes. Phosphorus is the key energy currency in cells (as part of ATP). It is also an important structural component of nucleic acids and some proteins, the basis of a key regulatory mechanism in signal transduction pathways, a component of membrane lipids, and (along with calcium) forms the mineral structure of bones and teeth. Finally, sulfur is found in two essential amino acids (methionine and cysteine) as well as two post-translational variants with central roles in core metabolism (homocysteine and taurine). The ability of cysteine residues to form disulfide bridges is critical to the structural integrity of many proteins. Sulfur is also found in coenzyme A, which is needed for carbohydrate and fatty acid metabolism, as well as providing the thiol group in many other reactions.

Micronutrients

Micronutrients are required in small quantities (generally less than 100 mg/day) and are divided into organic

molecules (vitamins) and inorganic molecules (microminerals). Vitamins are organic substances that (a) are not carbohydrates, amino acids, or fats, and (b) cannot be manufactured by the body in sufficient amounts in all circumstances and must therefore be obtained from the diet. There are 13 human vitamins, although some are represented by a small family of interconvertible molecules rather than a single substance. Most are required because humans lack the metabolic capability to produce them, although vitamin D is an exception because it is produced in the skin during exposure to UVB irradiation albeit not always in sufficient quantities to make dietary sources unnecessary. Vitamins are classified as either water soluble or fat soluble. In humans, there are four fat-soluble vitamins (A, D, E, and K), which are transported throughout the body in fat globules and stored in the liver and other fatty tissues, and nine water-soluble vitamins (eight B vitamins and vitamin C) that are not stored in the body and must be replaced every day.

Minerals that are required at levels below 100–200 mg/day are known as microminerals or trace minerals (Table 2) and these are required in minute amounts usually because they are required for the catalytic activity of a small number of specific enzymes. However, certain microminerals have more significant roles [4]. For example, iron can act as both an electron donor and acceptor, and in this context forms the functional core of the heme complex, which is found in the oxygen-binding molecules hemoglobin and myoglobin, and in the catalytic center of cytochromes (enzymes that carry out redox reactions). Iron is therefore required for oxygen transport in the body and for energy metabolism, also contributing to the catalytic activity of a range of nonheme enzymes such as ribonuclease reductase. Zinc also has multiple functions – it is an essential component of hundreds of enzymes (e.g., carboxypeptidase, liver alcohol dehydrogenase, and carbonic anhydrase) as well as transcription factors (zinc fingers and related molecules) and signaling proteins. The roles of other microminerals are more specialized and are discussed below.

Facultative Nutrients

The eight essential amino acids are needed by everyone. In addition, cysteine, tyrosine, histidine, and arginine

are essential for infants and children because they are required in large amounts for growth and development, and that demand cannot be satisfied without a dietary source [5]. For the same reason, children have greater requirements for the essential fatty acids than adults, although these are not facultative because they are also essential nutrients in adults despite being required in lower quantities. The amino acids arginine, cysteine, glycine, glutamine, histidine, proline, serine, and tyrosine are also considered conditionally essential, meaning they are not normally required in the diet, but must be supplied to specific populations that do not synthesize them in adequate amounts [7].

It is sometimes more convenient to define the essentialness of amino acids on a group basis in the same way as the essential fatty acids, since interconversion is possible within a group but no member of that group can be synthesized *de novo*. This applies to the sulfur-containing amino acids methionine, homocysteine, and cysteine, and to the aromatic amino acids phenylalanine and tyrosine. Likewise, arginine, ornithine, and citrulline, which are interconvertible within the urea cycle, can be considered as a group for nutritional purposes.

Nutrient Deficiencies

The lack of essential nutrients causes widespread malnutrition, a hidden problem in many communities because its effects are often subclinical or affect physical and cognitive development in a cumulative manner. Micronutrient deficiencies in particular have been referred to as “hidden hunger”; such deficiencies occur on a population-wide basis when the diet lacks diversity or is overly dependent on a single staple food [4], but in individual cases may reflect a genetic abnormality that prevents nutrient absorption or metabolism. Some important nutrient deficiencies and disorders are discussed below.

Macronutrient Deficiencies and Disorders

A lack of carbohydrates in the diet leads to a calorie deficit and results in hunger, then eventually catabolism and atrophy as the body uses its own tissues as a source of energy to maintain essential functions. These are the early signs of starvation, and can result in permanent organ damage and ultimately death. Besides

this general process, there are several specific disorders of carbohydrate metabolism such as galactosemia and glycogen storage diseases, which reflect an inability to break down or synthesize particular carbohydrates. As in the case for carbohydrates, a general deficiency in fats results in a calorie deficit, which if prolonged results in the symptoms of starvation. Deficiencies for essential fatty acids occur rarely, and mostly in infants. The symptoms include scaly dermatitis, alopecia, hair loss, thrombocytopenia, and stunted growth. The symptoms can be reversed by supplying adequate quantities of omega-3 and omega-6 fatty acids in the diet.

The essential amino acids are components of many proteins, so the symptoms associated with deficiency are often quite general. In adulthood, amino acid deficiencies may result in tiredness, inability to concentrate, irritability, bloodshot eyes, and in the longer term stunted growth, hair loss, anemia, connective tissue defects, inefficient wound healing, and reproductive problems. Acute amino acid deficiencies in childhood are more severe and result in a disease called kwashiorkor which involves swelling of the feet and abdomen, anorexia, ulcerating dermatoses, loss of hair, nails, and teeth, an enlarged fatty liver, and irritable behavior. It is possible that the symptoms of kwashiorkor may also be caused in part by concomitant micronutrient deficiencies and in some cases by poisoning. The disease also affects the immune system, often rendering children incapable of producing antibodies against vaccines.

As well as deficiency diseases, there are also several disorders of amino acid metabolism that need special dietary provisions. These include phenylketonuria (PKU), in which the enzyme phenylalanine hydroxylase is missing so phenylalanine cannot be converted into tyrosine, and maple syrup urine disease (MSUD), in which the body is unable to use the amino acids isoleucine, leucine, and valine.

Vitamin A Deficiency

Vitamin A in its reduced form (retinal) is required for the production of rhodopsin in the eyes, and helps to maintain epithelial and immune cells (making it necessary for a healthy immune system). In its acidic form (retinoic acid), it is a morphogen in development. Although many foods are said to be good sources of

vitamin A, it should be noted that these generally do not contain retinal itself but derivatives that can be converted into retinol and then into either retinal or retinoic acid. Meat and dairy sources of vitamin A primarily contain an esterified form called retinyl palmitate, whereas plants produce pro-vitamin A carotenoids such as β -carotene that are cleaved to produce retinol. These are abundant in a wide variety of dark green, yellow, and orange fruits; and vegetables such as oranges, broccoli, spinach, carrots, squash, sweet potatoes, and pumpkins [8].

Vitamin A deficiency (VAD) causes night blindness, i.e., the deterioration of light sensitive cells (rods) essential for vision in low light intensity and it can also damage the cornea resulting in a total form of blindness called xerophthalmia. The lack of vitamin A has a particularly severe effect on the immune system leaving individuals susceptible to infections [4]. More than four million children worldwide exhibit signs of severe VAD, including 250,000–500,000 per year that become partially or totally blind [9]. During pregnancy, women have a higher demand for vitamin A, and VAD in pregnancy causes nearly 600,000 deaths every year [9].

Vitamin B Group Deficiencies

The vitamin B complex comprises eight distinct molecules with different properties and functions. Vitamin B₁ (thiamine) is a coenzyme in carbohydrate metabolism, with the triphosphate derivative particularly active in neurons. Deficiency causes beriberi, a nervous system disorder resulting in weight loss, various degrees of amnesia and psychosis (in its severest form known as Korsakoff's syndrome), impaired perception, limb weakness, arrhythmia, and swelling, possibly leading to heart failure and death.

Vitamin B₂ (riboflavin) is the central component of the important enzyme cofactors flavin adenine dinucleotide (FAD) and flavin mononucleotide (FMN), whereas vitamin B₃ (niacin) is converted into the cofactors nicotinamide adenine dinucleotide (NAD) and its phosphate derivative NADP. Therefore, both vitamins are required in many enzymes that take part in carbohydrate, fat, and protein metabolism as well as other functions. Riboflavin deficiency causes ariboflavinosis, which is characterized by sensitivity to light, cracked

lips, dermatitis, and swelling of the tongue, pharyngeal and oral mucosa, and genitals. Niacin deficiency causes pellagra, which has varied symptoms including diarrhea, dermatitis, insomnia, fatigue, and mental confusion leading in severe cases to dementia. Vitamin B₅ (pantothenic acid) is needed for the synthesis of coenzyme A (CoA), and is therefore critical in the metabolism and synthesis of carbohydrates, proteins, and fats. Deficiency is rare and complete deficiency in humans has not been observed. Vitamin B₆ (pyridoxal, pyridoxine, or pyridoxamine) helps to balance sodium and potassium levels; it is also the precursor of pyridoxal phosphate, a cofactor required for the synthesis of heme and several important neurotransmitters. Deficiency may therefore lead to anemia due to the lack of heme, depression due to its impact on neurotransmitter production, high blood pressure and water retention due to the impact on electrolyte balance, and also elevated levels of homocysteine. Vitamin B₇ (biotin) is a coenzyme in the metabolism of fatty acids and leucine, and it plays a role in gluconeogenesis. Deficiency may lead to stunted growth and neurological disorders in infants. Vitamin B₉ (folic acid) is the source of tetrahydrofolate which is essential in DNA synthesis and many other core metabolic reactions. Deficiency in adults causes macrocytic anemia and elevated levels of homocysteine, but the impact in pregnant women is much more severe, leading to neural tube defects in the fetus. Spina bifida, in which bones of the spine do not completely enclose the spinal cord, is the most common congenital abnormality associated with folate deficiency [10]. Vitamin B₁₂ (cobalamin) is involved in the regeneration of folate, which means that deficiency in many cases mimics folic acid deficiency and can be alleviated by folate in the diet. However, it is also the cofactor for two specific (non-folate-dependent) enzymes, methylmalonyl coenzyme A mutase (MUT), and 5-methyltetrahydrofolate-homocysteine methyltransferase (MTR). Therefore, even in the presence of adequate folate, cobalamin deficiency can result in the failure of these reactions, leading to the accumulation of metabolites that weaken and destabilize myelin, resulting in neurological symptoms associated with demyelination. Finally, choline is a B vitamin that has three primary roles: structural integrity and signaling in cell membranes, cholinergic neurotransmission (acetylcholine synthesis), and the provision of methyl

groups via its metabolite, trimethylglycine (betaine), for the synthesis of S-adenosylmethionine. Choline deficiency is rare because, like vitamin D, humans can synthesize some choline although not always adequate amounts.

Vitamin C Deficiency

Vitamin C (ascorbic acid) is a powerful electron donor (antioxidant) and a cofactor in several metabolic pathways, including those forming the mature form of collagen. It plays an important role in the synthesis and stabilization of neurotransmitters, and also reduces iron compounds, enhancing the gastrointestinal absorption of dietary nonheme iron [11]. Insufficient vitamin C in the diet causes scurvy, which involves the breakdown of connective tissue fibers and muscular weakness [11]. High levels of vitamin C are found in citrus fruits and green vegetables [4].

Vitamin D Deficiency

Vitamin D is required for normal calcium and phosphorus homeostasis. It is a ligand that, when bound to its receptor, acts as a transcription factor controlling genes that affect calcium and phosphorus absorption; it is therefore particularly important for bone growth and maintenance. Deficiency results in impaired bone mineralization, which leads to bone-softening diseases such as rickets, a childhood disease characterized by stunted growth and deformity of the long bones, and osteomalacia, an adult bone-thinning disorder characterized by proximal muscle weakness and bone fragility, with chronic musculoskeletal pain.

Vitamin E Deficiency

Vitamin E is a group of compounds with powerful antioxidant activity. It protects fatty acids, low-density lipoproteins (LDLs), and other components of cell membranes from oxidation by free radicals [4]. Although it protects all cells, vitamin E is particularly important in red blood cells and neurons, so severe vitamin E deficiency results in anemia and neurological problems associated with nerve degeneration in the hands and feet. Vegetable oils, nuts, and green leafy vegetables are the major sources of vitamin E, and the consumption of foods rich in vitamin E is thought to reduce the risk of cancer, cardiovascular disease, and cataracts [4].

Vitamin K Deficiency

Vitamin K is a group of fat-soluble vitamins derived from 2-methyl-1,4-naphthoquinone that are needed for γ -carboxylation, a form of protein posttranslational modification. This is particularly important for the formation of the calcium-binding Gla domain, which is present in several blood-clotting proteins and osteocalcin. Vitamin K deficiency therefore affects blood coagulation as well as bone mineralization. Vitamin K1 (phylloquinone) needs to be sourced from the diet whereas vitamin K2 (menaquinone) is produced by bacteria in the large intestine and deficiency is rare except in malabsorption disorders or in patients with reduced gut flora (e.g., after treatment with broad-spectrum antibiotics). There are also several synthetic forms of the vitamin.

Iron Deficiency and Toxicity

Iron is the component of heme that binds oxygen, allowing oxygen to be transported from the lungs to peripheral tissues as part of oxyhemoglobin and carbon dioxide to be transported in the opposite direction. Iron also acts as an intracellular electron transporter to transfer energy (especially to the mitochondria) and it is a part of enzyme systems involved in the synthesis of hormones and neurotransmitters [4]. Iron deficiency is the most widespread nutritional disorder in the world, affecting an estimated 1.2 billion people [12]. In children, low iron intake is associated with cognitive dysfunction whereas in adults it causes iron deficiency anemia (IDA), oxidative DNA damage, reduced immunity, and (in pregnant women) premature births/low birth weight [12]. The true prevalence of iron deficiency in a population is greater than the level of clinically detectable IDA because most individuals are likely to be iron deficient long before a detectable drop in hemoglobin levels [12]. Iron deficiency is often caused by inadequate intake, but it can also result from the consumption of antinutritional molecules such as phytic acid/phytate which inhibit the uptake of bioavailable iron even if sufficient amounts are present in the diet. Foods rich in phytate include many cereal grains, so people with cereal-rich diets are particularly susceptible to iron-deficiency diseases.

The upper limit for iron consumption is 25–50 mg/day. Symptoms of iron toxicity include fatigue,

anorexia, dizziness, nausea, vomiting, headache, weight loss, shortness of breath, and possibly a grayish color to the skin [13]. Chronic excess iron intake results in symptoms such as liver cirrhosis, diabetes, and heart failure, and can promote some cancers. Acute overdose (e.g., iron supplements) is toxic and may induce gastrointestinal side effects as well as causing secondary hemochromatosis [13].

Zinc Deficiency and Toxicity

Zinc is a key functional component of over 300 enzymes and also coordinates the functional domains of numerous transcription factors. Zinc deficiency therefore affects many aspects of metabolism and gene expression, and has notable detrimental effects on the immune system, basal metabolism, and development, particularly spermatogenesis and testosterone steroidogenesis [14]. Severe and prolonged zinc deficiency in humans reduces appetite and bone growth, delays sexual maturation, causes skin lesions, diarrhea, and alopecia (hair loss), and reduces the ability of the cellular immune system to fight infections [14]. Zinc, like iron, is affected by the amount of phytate in the diet, so deficiency is particularly prevalent in populations that subsist on cereal-rich diets.

The upper level of Zn intake in adults is 45 mg/day, although tolerance is lower in women, children, and the elderly. Excessive long-term zinc intake interferes with iron and copper metabolism, so the symptoms of zinc toxicity overlap with those of iron and copper deficiency, e.g., anemia, neurological symptoms, and lower immunity [14]. Excessive levels of zinc also affect the relative levels of LDL and HDL cholesterol and increase the risk of cardiovascular disease [14].

Iodine Deficiency and Toxicity

Iodine is an essential component of the thyroid hormones thyroxine (T4) and triiodothyronine (T3), whose function is to increase the basal metabolic rate (therefore affecting carbohydrate, fat, and protein metabolism), stimulate protein synthesis, regulate long bone growth in concert with growth hormone, stimulate neuronal maturation, and regulate how cells respond to catecholamines [15, 16]. For some of these functions, iodine acts in concert with iron, zinc, and selenium [16]. Iodine deficiency disorder (IDD)

generally reflects a lack of iodine in the soil, which places more than 1.5 billion people in the world at risk, particularly children and pregnant or lactating women [4, 15]. The initial effects of IDD are to suppress the synthesis of thyroid hormones, which leads the pituitary gland to produce more thyroid-stimulating hormone and causes the thyroid to enlarge in an attempt to capture more iodine from the blood. This condition, known as goiter, can be reversed by iodine supplementation (see below). The effects of long-term iodine deficiency in pregnancy and childhood cannot be reversed – these include stunted physical and mental development, resulting in a condition known as cretinism [16].

Iodine toxicity is unusual because a daily intake of 1 mg or more appears to be safe. However, where there is prolonged excessive consumption or an underlying disease that prevents iodine metabolism, the excess iodine can inhibit thyroid hormone synthesis, a phenomenon known as the Wolff–Chaikoff effect [4].

Selenium Deficiency and Toxicity

Selenium is a component of the nonstandard amino acids selenocysteine and selenomethionine, which are required for the activity of a number of enzymes (selenoenzymes) such as glutathione peroxidase, tetraiodothyronine 5' deiodinase, thioredoxin reductase, formate dehydrogenase, and glycine reductase. Its presence in thyroid hormone deiodinase means that selenium is necessary for the normal function of the thyroid gland. Many of the other selenoenzymes act as antioxidants with a range of protective roles in the body, helping to prevent cancer and cardiovascular disease, often in concert with vitamin E [4, 16, 17]. Selenium may also play a role in the regulation of other micronutrients, such as iron and zinc [16].

Selenium deficiency can lead to Keshan disease, a potentially fatal cardiomyopathy associated with increased susceptibility to infectious diseases, and also Kashin–Beck disease (usually if selenium and iodine deficiency occur concurrently) which is characterized by cartilage atrophy and necrosis leading to damaged joints [4, 18]. Selenium deficiency is unusual, but occurs where the mineral is particularly scarce in the soil, as in some parts of China. Interestingly, in other parts of China, the soil is so rich in selenium

(>9% selenium content) that eating corn grown on this soil can result in acute selenium toxicity (selenosis). The maximum safe dietary intake of selenium is thought to be 400–800 µg/day, and most people consume only 10% of this amount, but in villages surrounding this selenium-rich area, a typical diet yields 3,200–6,690 µg of selenium per day, which is 100-fold the normal level. In these villages, morbidity can approach 50% with typical symptoms including a garlic-like odor to the breath, gastrointestinal disorders, loss of hair and nails, fatigue, irritability, and progressive neurological damage, leading eventually to liver cirrhosis and death [4, 18].

Other Microminerals

Whereas iron, zinc, iodine, and selenium are the “big four” micronutrients with diverse functions in the body, a variety of additional mineral ions are required for specific purposes. Copper is an essential component of several enzymes including cytochrome c oxidase, cobalt is a component of vitamin B₁₂, manganese is an essential cofactor for enzymes such as the antioxidant superoxide dismutase, molybdenum is a component of several redox enzymes, and nickel is present in urease. Fluorine is a special case in that it is not essential for life, but the addition of fluoride to drinking water helps to prevent dental caries, so it certainly contributes to human health and well-being. Other minerals, such as boron, vanadium, silicon, and arsenic, are thought to have biological roles although this has yet to be demonstrated in humans. Many of these microminerals are known to cause rare deficiency disorders as well as toxicity effects. Chronic copper deficiency, e.g., has multiple effects on metabolism because the corresponding enzymes cannot function, and also leads to anemia because copper is required for efficient iron absorption. Excess copper competes with zinc so the symptoms overlap with zinc deficiency, but acute copper toxicity is rare other than in individuals with metabolic disorders due to the efficiency of copper secretion.

Responses to Malnutrition

The most effective intervention to alleviate micronutrient malnutrition is the implementation of a varied diet including fresh fruit, vegetables, fish, and meat. This is impractical in many countries because food is

not widely available, but even where fresh food is abundant, there can be compliance issues that result in persistent low-level malnutrition. Where infrastructure allows, micronutrient nutrition can be improved using supplements (usually in tablet/sachet form) or conventional fortification (where micronutrients are added to processed foods, such as packaged cereals). Unfortunately, such strategies have been largely unsuccessful in developing countries because of insufficient funding, poor governance, and a poor distribution network. There has been some success in a limited number of cases discussed later, including mineral fortification (iodized salt) and vitamin supplementation (vitamin A), although coverage has been incomplete. Developing country governments must address the risk of micronutrient malnutrition and should actively participate in the establishment of intervention programs, seeking international expertise and assistance where necessary. A more recent development is biofortification, where intervention takes place before plants are harvested. Different strategies to alleviate micronutrient malnutrition have been ranked according to their cost-effectiveness by the Copenhagen Consensus, a panel of expert economists that decide the most cost-effective strategies for addressing global challenges (Table 4). In this section, the different interventions for improving micronutrient nutrition are summarized, mainly in the context of developing countries where malnutrition has the greatest impact.

Emergency Measures (Short-Term Relief): Supplementation Programs

Supplementation is the distribution of pills or mineral solutions for immediate consumption and is the most effective short-term intervention to improve nutritional health. Supplementation helps to alleviate acute mineral shortages but is unsustainable for large populations and should be replaced with fortification at the earliest opportunity [19]. In developed countries, where mineral malnutrition is rare, supplementation is focused on a small subset of the population with specific deficiencies resulting from medical conditions. In developing countries, where acute and chronic deficiencies are commonplace, supplementation is highly recommended as a complement to the diet (fortified or otherwise) for the entire population. Supplementation

Biotechnology and Nutritional Improvement of Crops.

Table 4 Copenhagen Consensus Center strategies [23].

The Copenhagen Consensus Center is a think-tank based in Denmark that advises governments and philanthropists about the best ways aid and development money can be used to address the world’s greatest challenges. Currently, strategies to address malnutrition represent five of the top ten strategies providing the best value

Rank	Solution	World’s greatest challenges
1	Micronutrient supplements for children (vitamin A and zinc)	Malnutrition
2	The Doha development agenda	Trade
3	Micronutrient fortification (iron and salt iodization)	Malnutrition
4	Expanded immunization coverage for children	Diseases
5	Biofortification	Malnutrition
6	Deworming and other nutrition programs at school	Malnutrition and Education
7	Lowering the price of schooling	Education
8	Increase and improve girls’ schooling	Gender equality
9	Community-based nutrition promotion	Malnutrition
10	Provide support for women’s reproductive role	Gender equality

has also been recommended by WHO, the World Food Program (WFP), and UNICEF [20] for extreme situations such as refugee camps, where it can also help to address diseases such as acute diarrhea.

The distribution of vitamin A supplements has been one of the most cost-effective and successful acute intervention programs in the developing world [19], but this is a rarity. Like fortification, successful supplementation strategies require a robust infrastructure and a government determined to improve the nutritional health of its population [19]. Supplementation requires compliance monitoring because people often neglect to take regular supplements at prescribed intervals. For example, in some communities with both

chronic iodine deficiencies and no access to iodized salt, the distribution of iodine capsules to women is a short-term but more expensive measure to avoid IDD [21]. Many studies have shown that zinc supplements are beneficial, particularly in areas with zinc-depleted soil [4, 22]. Zinc supplementation has been adopted by WHO and UNICEF in their guidelines for the treatment of acute diarrhea [20]. Zinc supplements are normally formulated as tablets or as oral rehydrated solutions, requiring the active compliance of families and communities. The supplements must be administered frequently, and may be more efficient when other micronutrients such as vitamin A are administered simultaneously [14, 19].

**Long-Term Measures (Sustainable Relief):
Fortification Programs**

Food fortification is one of the most cost-effective long-term strategies for micronutrient nutrition [23] and ranks third in terms of cost-benefit balance according to the Copenhagen Consensus (Table 4). Fortification takes place during food processing and increases the product price. These factors make fortified products unaffordable to the most impoverished people living in remote rural areas. Even in more accessible areas, fortification requires government awareness and policies for implementation and compliance monitoring. The Flour Fortification Initiative (FFI) claims that food fortification must be implemented at a national level to be successful, and must involve the public, private business and government sectors. The FFI supports mandatory fortification based on scale, equity, business, cost, and sustainability. The creation of partnerships among countries with established fortification policies would help other countries to establish their own infrastructure. Although the implementation of mandatory fortification would take time, there are enormous benefits for the country and its population [24].

Before considering case studies, it is important to note that food fortification targets must be selected carefully. Research must be carried out to identify the best vehicles to deliver micronutrients, i.e., those with the widest and most frequent consumption reflecting the staple diet of individual countries and/or regions. Also, a suitable fortification agent must be identified – one

that is stable but easily mobilized in the gut, one that does not alter the quality of the food to which it is added, and one that can be stored and distributed easily. Since many parts of the world suffer from multiple deficiencies, strategies must also be developed to fortify foods simultaneously with several micronutrients, without adverse interactions among them. The addition of a single micronutrient would have approximately the same cost implications as the addition of several, but more research is needed to determine the most cost-effective way to make nutritionally complete foods [23, 24].

Iodization of Salt Iodine fortification of salt is one of the nutrition success stories of the twentieth century, helping to eliminate IDD in many parts of the world. Even though alternative food vehicles have been proposed, salt is thus far the most economical and sustainable fortification target. In 1990, 20% of households in the developing world consumed iodized salt. In 1994, WHO and UNICEF recommended mandatory salt iodization in all countries to ensure consumption and prevent access to unfortified salt. By the year 2000, iodized salt had reached 70% of households in the developing world. Although some countries still lack access to iodized salt, the reach is improving all the time, with many countries becoming self-sufficient and no longer needing donations to support their fortification programs [25]. Countries with no nutrition policies or monitoring are the main challenges for intervention strategists, because fortification requires external funding and IDD reappears if salt iodization is discontinued.

Organizations such as WHO, UNICEF, and The International Council for the Control of Iodine Deficiency Disorders (ICCIDD) have created and distributed guidelines for the implementation of iodine fortification. They work together to eliminate iodine deficiency through the Universal Salt Iodization (USI) in partnership with the Micronutrient Initiative (MI), the World Bank, Kiwanis International, and with public and private sector involvement including consumer organizations, schools, and medical authorities around the world.

Iron and Folate Fortification of Wheat Flour Another successful fortification approach is the

inclusion of minerals in wheat flour, so that widely consumed products such as bread become nutritionally beneficial as well as providing calories. Indeed, bread is often double fortified with iron and folate, most recently in Iran [26]. The mandatory fortification of wheat flour has been established in several developing countries in Latin America, leading to a reduction in IDA [19]. The FFI has created a network that involves the participation of public, private, and government sectors, resulting in an increase in the global prevalence of iron-fortified wheat flour from 18% in 2004 to 27% in 2007, helping 540 million people to avoid IDA [26]. The MI also supports this strategy and works with FFI in developing countries.

Iron fortification can be technically challenging because iron compounds that are easily absorbed by the gut tend to leach easily and also change the taste of food, whereas those with less impact on taste are the most difficult to absorb [27, 28]. Encapsulation has been investigated as a potential solution and this is an active area of current research [29].

Other Examples Zinc fortification has been implemented in the industrialized world but rarely in developing countries. One exception is zinc-fortified wheat and corn flour in Mexico, which is used to make bread and tortillas, the two principal staples [30]. Organizations such as the Zinc Task Force (ZTF) and the International Zinc Nutrition Consultative Group (IZINCG) are fighting zinc deficiency by promoting diverse strategies to eliminate it. As zinc and iron deficiency tend to go hand in hand, it has been suggested that double fortification would be effective with little additional cost, particularly if iron fortification were already in place.

Selenium-fortified products such as salt, margarine, cereals, and soft drinks have been produced although not widely distributed [18]. Salt fortified with selenium has been used in parts of China where the soil is naturally depleted but it has not been supported to the same degree as iodized salt [17]. The multi-micronutrient fortification of biscuits with iron, zinc, iodine, and vitamin A has been implemented with Vietnamese schoolchildren, reducing the risk of IDA, IDD, and VDA, and increasing the effectiveness of deworming [31].

Long-Term Measures (Sustainable Relief): Biofortification

Conventional interventions have a limited impact, so biofortification has been proposed as an alternative long-term approach for improving nutrition [23, 32]. Biofortification focuses on enhancing the micronutrient qualities of crops *at source*, encompassing processes that increase both micronutrient levels and their bioavailability in the edible parts of staple crops. The former can be achieved by agronomic intervention (in the case of minerals), plant breeding or genetic engineering, whereas only plant breeding and genetic engineering can influence nutrient bioavailability.

Plant breeding and genetic engineering are often regarded as similar means to achieve a common goal because, in contrast to agronomic interventions, both involve changing the genotype of a target crop. The two processes are similar in aim, albeit different in scope. Both attempt to create plant lines carrying genes that encourage the efficient accumulation of bioavailable micronutrients – plant breeding achieves this by crossing the best-performing plants and selecting those with favorable traits over many generations, whereas genetic engineering accesses genes from any source and introduces them directly into the crop. Plant breeding is restricted to genes that can be sourced from sexually compatible plants and the limited amount of genetic variability therein, whereas genetic engineering has no taxonomic constraints and even synthetic genes can be used.

The main advantage of genetic engineering and plant breeding approaches for mineral enhancement is that investment is only required at the research and development stage, and thereafter the nutritionally enhanced crops are entirely sustainable. Furthermore, as stated above, mineral-rich plants tend to be more vigorous and more tolerant of biotic stress, so the overall yields are likely to improve in line with mineral content [27]. Unlike conventional intervention strategies, genetic engineering and plant breeding are both economically and environmentally sustainable. A combination of both strategies has also been proposed [33] and can produce significant synergic improvements compared to each strategy applied individually [34]. Although there are no commercial nutritionally enhanced plants derived from either method at the current time, this approach has the greatest cost-effectiveness in the long

term and is likely to have the most important impact over the next few decades.

Biofortification is also likely to be more accessible than conventional interventions in the long term because it removes hurdles such as the reliance on infrastructure and compliance. Moreover, plants assimilate minerals into organic forms that are naturally bioavailable and contribute to the natural taste and texture of the food. Economic studies have shown the many potential health benefits of biofortification, especially in combination with conventional strategies [35].

Nutritional Improvement Through Agronomic Approaches

Farmers have applied mineral fertilizers to soil for hundreds of years in order to improve the health of their plants, but within certain limits the same strategy can also be used to increase mineral accumulation within cereal grains for nutritional purposes. This strategy only works if the mineral deficiency in the grain reflects the absence of that mineral in the soil, and if the mineral fertilizer contains minerals that can be mobilized rapidly and easily. Also, even if plants can absorb minerals efficiently from the soil, they may store the mineral in inedible organs (e.g., leaves but not fruits or seeds), or they may accumulate the mineral in a form that is not bioavailable, thus having no impact on nutrition [27].

In industrialized countries such as Finland and New Zealand, this strategy has been applied successfully to increase the amount of selenium in the diet [18]. It is difficult to apply to iron, because most of the inorganic iron in the soil is inaccessible to plants. Like supplements and fortification, agronomic intervention is probably best applied in niche situations or in combination with other strategies [36].

One drawback of agronomic intervention in developing countries is the cost and impact of fertilizers. Fertilizer use increases the cost of food, thus reducing its availability to the most impoverished people. To be effective, fertilizers must be applied regularly, but impoverished farmers would be under financial pressure to “cut corners” to save costs, even though seeds produced from mineral-rich soil tend to germinate more vigorously than those in poor soils, thus increasing yields [36].

Iodine fertilizers have received comparatively little attention due to the success of fortification programs,

but they have been used in regions of China where the soil has low iodine levels. The addition of iodine to irrigation water (fertigation) in China has successfully increased the level of iodine in rice, but despite the technical success such projects have not addressed IDD due to poor infrastructure [16]. Iron has a very low mobility in soil because it binds rapidly to soil particles when applied as fertilizer in the form of FeSO_4 . It is converted rapidly from Fe^{2+} to Fe^{3+} under these circumstances, rendering it unavailable for absorption [27]. In poor soils lacking the macronutrients nitrogen, phosphorus, and potassium, the application of NPK fertilizers can promote the capture of iron, although this also depends on the soil pH. Alkaline conditions in the rhizosphere prevent the uptake of iron and zinc, whereas slightly acidic soil promotes the absorption of these minerals [27]. Foliar sprays of FeSO_4 or chelates allow the direct uptake of iron.

Unlike iron, zinc is very mobile in soil and is easily absorbed, especially under slightly acidic conditions. Zinc fertilizers such as ZnSO_4 can increase the yield of cereals and legumes in zinc-deficient soils, and can also increase zinc levels in the grain (although this is dependent on genotype). Zinc fertilization has been used in Turkey, where NPK fertilizers are enriched with zinc and applied normally for crop production. Soils in Turkey are extremely deficient in zinc and this program has successfully increased plant growth and yield. Although it is likely that the population has benefited from the nutritional properties of crops grown with zinc fertilizers, no population studies have yet been carried out to determine the impact on human health [36].

Finally, selenium provides probably the most successful example of agronomic intervention by mineral fertilization because it fulfills the three major requirements for such a strategy to work: (1) sodium selenate is highly mobile in many soil types; (2) it is absorbed easily by plants and, in the case of cereals, accumulates in the grain; and (3) it accumulates in a readily bioavailable form, selenomethionine [17]. As is the case for zinc, selenium added to NPK fertilizers has been used successfully in Finland and New Zealand to increase the selenium content of grains, with a positive impact on the general health and well-being in the population [18].

Nutritional Improvement Through Conventional Breeding

Plant breeding programs focus on improving the level and bioavailability of nutrients in staple crops using their natural genetic variation [37]. The HarvestPlus program was established by the Consultative Group on International Agricultural Research (CGIAR) to improve human nutrition by breeding new varieties of the staple food crops consumed by the poor. It is a global alliance of institutions such as the International Rice Research Institute (IRRI), the Centro Internacional de Mejoramiento de Maíz y Trigo (CIMMYT), the Centro Internacional de Agricultura Tropical (CIAT) and the International Institute of Tropical Agriculture (IITA) and other academic institutions world-wide. Its aims include the discovery of genetic variation affecting heritable mineral traits, verification of its stability under different conditions and the feasibility of breeding to increase mineral content in edible tissues without affecting yields or other quality traits. Feasibility data, mainly for iron and zinc, has been collected and a summary has been published [38].

Although breeding for increased mineral levels is more sustainable than conventional interventions, no high-mineral varieties have been introduced to the market thus far. This reflects the long development times, particularly if the mineral trait needs to be introgressed from a wild relative. Breeders utilize molecular biology techniques such as quantitative trait locus (QTL) maps and marker-assisted selection (MAS) to accelerate the identification of high-mineral varieties, but they have to take into account differences in soil properties (e.g., pH, organic composition) that may interfere with mineral uptake and accumulation. For example, the mineral pool available to plant roots may be extremely low in dry, alkaline soils with a low content of organic matter [36].

Conventional breeding could also be useful for the enhancement of organic nutrients, although there has been no coordinated international effort to achieve progress in this area. Even so, crosses between inbred lines have been used to identify QTLs affecting carotenoid and tocopherol levels in corn [39], as well as carotenoid levels in carrot and tomato [40], and these could be used in the future for nutritional improvement programs. Recently, natural genetic variation at several loci in corn has been

exploited to generate lines with increased levels of specific carotenoids [41, 42].

Although some variation in iodine content has been found in staple crops [43], the focus remains on manual intervention strategies because salt iodization has been so successful. However, the HarvestPlus initiative has proposed the inclusion of iodine in its program because of widespread iodine deficiency in some countries and the interaction between iodine and other micronutrients (mainly iron, zinc, and vitamin A [16]). Iron and zinc levels vary significantly in many crops, and CGIAR is looking into the possibility of breeding high-mineral varieties of cereals using this genetic diversity. The amount of iron in rice grains varies between 6 and 22 mg kg⁻¹, whereas in corn it varies between 10 and 160 mg kg⁻¹, and in wheat the range is 15–360 mg kg⁻¹ [44]. Zinc levels are similarly broad – between 14 and 61 mg kg⁻¹ in rice, 14 and 190 mg kg⁻¹ in wheat, and between 12 and 96 mg kg⁻¹ in corn [43, 44]. Despite this natural variation, commercial varieties of wheat still have low mineral levels compared to wild wheat, where the grain may contain up to tenfold the normal amount of zinc. Furthermore, wild emmer wheat accessions have been identified in which the seeds contain up to 139 mg kg⁻¹ zinc, up to 88 mg kg⁻¹ iron, and up to 380 g kg⁻¹ protein, as well as showing strong tolerance of drought stress and low zinc levels in the soil [44]. There also appears to be moderate genetic variation in the selenium content of modern cereals although wild wheat varieties, with higher selenium levels, are potential sources of additional diversity [43, 44].

Nutritional Improvement Using Biotechnology

The major advantages of genetic engineering over conventional breeding are the diversity of the potential sources of genetic information, the speed with which improved elite varieties can be generated and, perhaps most important, the fact that nutritional traits for different vitamins and minerals can be stacked in the same plant without highly complex breeding programs [32]. Genetic engineering currently offers the only opportunity to produce nutritionally complete staple foods.

Despite these advantages, there are no high-micronutrient, genetically engineered crops on the market thus far. Whereas with conventional breeding this reflects the long development phase, in the case of

genetic engineering this reflects the current uncertain regulatory environment, particularly trade barriers and differences in national regulatory systems that inhibit the production, transport, and use of transgenic products. Trade barriers for transgenic crops have been established de facto in the EU because of the precautionary approach to regulatory oversight, so developing countries (such as China and India) are pressured not to grow such products for export even though they may still benefit the domestic population by improving health and wealth [2, 3].

Biotechnology Strategies to Increase Nutritional Content

Many biotechnology strategies can be used to enhance the nutritional value of crops and these offer a rapid way to introduce such traits into elite varieties. The best approach for a given nutrient depends predominantly on whether the plant synthesizes the nutritional compound de novo or obtains it from the environment. Organic molecules such as amino acids, fatty acids, and vitamins are synthesized by the plant, and increasing the nutritional content therefore requires some form of metabolic engineering with the aim of increasing the amount of the desirable compound, decreasing the amount of a competitive compound (e.g., one that uses the same precursors but diverts them into a different pathway) or even extending an existing metabolic pathway to generate a product that is not usually made in that species [32]. In contrast, mineral nutrients are obtained from the environment and mineral enhancement therefore involves strategies to increase uptake, transport and/or to increase accumulation in harvestable tissues [23].

Increasing the Availability of Essential Amino Acids

Among the eight essential amino acids discussed above, methionine, lysine, and tryptophan are the most limiting in legumes and cereals, and since these are the major types of staple crops they are also the primary targets for nutritional enhancement. Generally, four strategies have been applied to increase the content of essential amino acids in plants: (1) mimicking natural mutants, (2) the expression of recombinant storage proteins with desirable amino acid profiles, (3) genetic engineering to enhance the free amino acid pool, and (4) combination approaches.

Mimicking Natural Mutants The naturally occurring *opaque2* mutant in corn has higher lysine and tryptophan levels than wild-type corn but has a soft, chalky kernel which is unsatisfactory for cooking. The higher content of essential amino acids in the mutant results from lower levels of certain storage proteins (e.g. α - and β -zeins) allowing other proteins (e.g. 27-kDa γ -zein) to replace them and increase the prevalence of the two limiting amino acids. Breeding programs have resulted in the development of quality protein maize (QPM) which benefits from the higher lysine and tryptophan levels of the *opaque2* mutant but combines this with a hard kernel for superior cooking qualities [45]. Although QPM has lower levels of α - and β -zeins compared to wild-type corn, it has higher levels of γ -zein. Zarkadas et al. [46] showed that QPM may provide up to 73% of human protein requirements, compared to 28–50% for common corn. Success with *opaque2* corn has stimulated extensive research to identify similar mutants in other cereals such as barley (*Hordeum vulgare*) and sorghum (*Sorghum bicolor*).

The *opaque2* corn mutants have inferior agronomic traits that cannot be overcome easily, but the laborious breeding program that gave rise to QPM can be replicated much more rapidly by genetic engineering. The transformation of corn with an RNAi construct to suppress target storage protein genes resulted in a phenocopy of the *opaque2* phenotype; transgenic seeds contained less α -zein than normal but higher levels of lysine [47, 48].

Expression of Recombinant Storage Proteins The main source of essential amino acids in sink tissues such as developing seeds is the storage proteins; therefore, one reason for the lack of certain amino acids in some staple crops is the absence of major storage proteins containing them. Thus, one of the main strategies for improving the levels of limiting amino acids is to express heterologous storage proteins that are rich in these specific amino acids.

One of the earliest attempts using this approach was the expression of pea legumin, which is rich in lysine, in rice endosperm, where lysine is limiting; in the best lines, heterologous legumin represented up to 4.2% of the total protein content [49]. Similarly, Stöger et al. [50] generated transgenic wheat plants expressing pea legumin using the low molecular weight (LMW) glutenin promoter, with legumin representing 1.5% of

total soluble protein in the best transgenic lines. More significant increases in lysine content have been achieved by modifying cereal storage protein genes before deployment to increase the number of lysine codons. For example, Jung and Carl [51] modified the barley hordothionine protein to include 12 lysine residues (hordothionine-12, HT12) and the barley high lysine protein to include eight lysine residues (barley high lysine-8, BHL8) and expressed them in corn along with the bacterial enzyme dihydrodipicolinate synthase (DHPS, see below). This resulted in a total lysine content of nearly 0.8%, about four times the level in wild-type seeds. The expression of HT12 in sorghum increased the lysine content by 50% compared to wild-type grain, and the expression of *sb401*, encoding another high-lysine storage protein, increased lysine levels in corn by 54.8% and total protein content by up to 39% [52].

Lysine levels can also be increased by expressing the animal equivalent of storage proteins, such as the nutritional proteins found in milk. The principle was established when porcine α -lactalbumin was expressed in corn and either targeted for secretion to the apoplast or for retention in the endoplasmic reticulum (ER), but individual amino acid levels were not reported [53]. More recently, Bicar et al. [54] repeated the experiment and showed that α -lactalbumin expression in corn increased the lysine content up to 47%. The lysine content of transgenic corn has also been increased up to 26% by expressing a heterotypical Arabidopsis lysyl tRNA synthetase, which inserts lysine residues in place of other amino acids during the synthesis of seed-storage proteins [55].

The expression of heterologous storage proteins has also been used as a strategy to increase the levels of methionine in transgenic crops, focusing on the 2S storage proteins which are unusually methionine rich. For example, expression of Brazil nut 2S albumin in soybean and narbon bean doubled the methionine content of the seeds, and increased methionine content by 33% in canola [56]. Similarly, the expression of sunflower 2S albumin increased total methionine content by up to sevenfold in potato tubers [57]. This approach does not always work well, e.g., the expression of the sunflower albumin SFA8 in rice and chickpea [58] merely redistributed the sulfur-containing amino acids (more methionine, less cysteine) with no

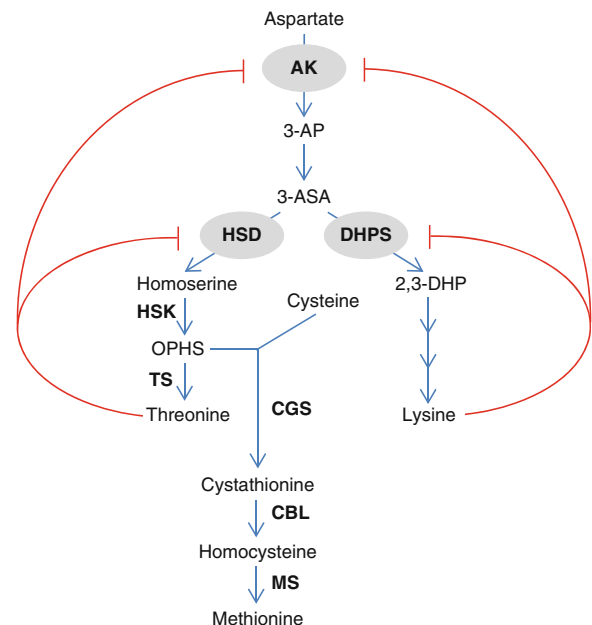
net improvement in nutritional properties. The 2S sulfur-rich albumins are allergenic in some human populations, reducing their usefulness for improving nutritional quality [59].

Ideally, a single protein would provide nutritional completeness in terms of essential amino acids. Grain from the pseudo-cereal amaranth (*Amaranthus hypochondriacus*) not only has a high protein content compared to traditional crops (17–19% of seed dry weight (DW) compared to ~10%), but that protein is rich in essential amino acids such as lysine (5%, more than twice the amount in wheat flour), threonine (2.9%), tyrosine (3.4%), and the sulfur-containing amino acids cysteine and methionine (4.4%). This provides a nutritional composition fairly close to the ideal as recommended by WHO, and the protein is not allergenic [5]. The cDNA for this protein has therefore been expressed in a number of crops with nutritionally incomplete proteins to increase overall protein levels and provide greater amounts of limiting amino acids. Rascón-Cruz et al. [60] expressed amaranthin in corn using the rice glutelin-1 promoter and increased the amount of protein by up to 32% while simultaneously boosting the levels of the three most limiting amino acids, lysine, tryptophan, and isoleucine. Chakraborty et al. [57] expressed the protein in potato tubers using the granule-bound starch synthase (GBSS) promoter, and increased total protein levels by up to 45%. Most recently, the protein was expressed in wheat using the LMW glutenin promoter with the amaranthin protein representing nearly 2.5% of total seed protein in some lines, increasing the levels of lysine to 6.4%, and tyrosine to 3.8% [61].

As well as natural heterologous storage proteins, completely synthetic proteins (i.e., proteins designed from first principles) can also be expressed to boost the levels of particular amino acids. For example, a synthetic protein matched to human amino acid requirements was expressed in cassava [62]. Even in these ideal cases, however, the levels of essential amino acids in the resulting transgenic crops tend to fall below expectations given the composition of the heterologous proteins. The inability of heterologous proteins to change the essential amino acid content of target crops abruptly and predictably often reflects the limited free amino acid pool, which provides the substrates for protein synthesis.

Engineering the Free Amino Acid Pool

In higher plants, lysine, threonine, and methionine are synthesized from aspartic acid via a pathway that is highly branched and under complex feedback control (Fig. 1) [63]. Two key enzymes are aspartate kinase (AK), which functions early in the pathway and is inhibited by both lysine and threonine, and dihydrodipicolinate synthase (DHPS), which is the first enzyme specifically committed to lysine biosynthesis and is inhibited by lysine alone. Feedback-insensitive versions of the bacterial enzymes have been expressed in model plants with encouraging results, e.g., the free lysine



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Figure 1

Synthesis of the essential amino acids lysine, threonine, and methionine [63]. The three key enzymes (gray circles) are aspartokinase (AK), dihydrodipicolinate synthase (DHPS), and homoserine dehydrogenase (HSD), all of which are subject to end-product feedback inhibition (red arrows). Abbreviations for substrates: 3-AP, aspartyl-3-phosphate; 3-ASA, aspartate semialdehyde; OPHS, O-phosphohomoserine; 2,3-DHP, 2,3-dihydrodipicolinate. Abbreviations for other enzymes: HSK, homoserine kinase; TS, threonine synthase; CGS, cystathionine- γ -synthase; CBL, cystathionine β -lyase; MS, methionine synthase. Multiple arrows indicate several unspecified reactions

content in tobacco and *Arabidopsis* seeds was increased by expressing feedback-insensitive DHPS [63]. Similarly, the expression of feedback-insensitive DHPS in corn embryos increased the levels of free lysine from <2% to almost 30% of the free amino acid pool, with concomitant increases in threonine [64]. Analogous approaches have increased the lysine levels in canola and soybean [65, 66]. However, high levels of lysine in all plant tissues can cause abnormal vegetative growth and flower development that reduce seed yield [63].

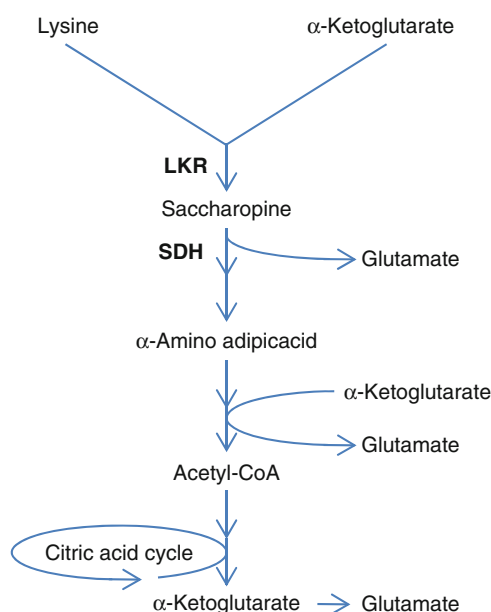
The increased accumulation of lysine in tobacco seeds correlated with the enhanced activity of a bifunctional enzyme, lysine-ketoglutarate reductase/saccharopine dehydrogenase (LKR/SDH), which controls the first two reactions of the α -amino adipic acid pathway of lysine catabolism (Fig. 2) [67, 68]. To determine the impact of lysine catabolism on the levels of free lysine in the amino acid pool, a feedback-insensitive DHPS was expressed in wild-type

Arabidopsis seeds and those of a LKR/SDH knockout mutant [69]. Whereas transgenic seeds without the mutation contained 12 times the normal levels of lysine, transgenic mutant seeds contained 80 times normal lysine levels, showing the importance of lysine catabolism in strategies to increase the accumulation of this amino acid. Similarly, it has been possible to cross transgenic corn lines where one parent expresses a feedback-insensitive enzyme for lysine synthesis that doubles the amount of free lysine [70] and the other expresses an RNAi construct against LKR/SDH thus inhibiting lysine catabolism [71]. In the double transgenic progeny, the amount of lysine was 40 times the level present in wild-type corn [64].

The major enzyme-controlling methionine synthesis is cystathionine γ -synthase (CGS), and its activity in *Arabidopsis* is under feedback control reflecting the abundance of the important metabolic intermediate S-adenosylmethionine (SAM) [72]. Mutations in the N-terminal portion of CGS that affect this feedback regulation result in methionine overproduction [72, 73], and this can be combined with the expression of a feedback-insensitive AK to increase methionine levels even further [74].

The expression of feedback-insensitive AK also increases the abundance of threonine. In some cases, the increases in threonine levels were matched by smaller, although still significant, increases in the levels of isoleucine, methionine, and lysine, indicating that AK activity is more important for threonine synthesis than it is for lysine synthesis [63].

Tryptophan synthesis in plants is strongly regulated by high levels of tryptophan inhibiting the enzyme anthranilate synthase, which catalyzes the conversion of chorismate to anthranilate. As is the case for other amino acids, a preferred strategy to overcome this limitation is the expression of a feedback-insensitive version of this key enzyme, as has been achieved in tobacco leaves and the roots of the forage legume *Astragalus sinicus* [75]. A mutant anthranilate synthase from rice has been shown to increase the amount of free tryptophan in transgenic rice seeds by over 400-fold [76], in potato tubers by approximately 30-fold [77], and in soybean seeds by approximately 20-fold [78]. A similar mutant gene from tobacco increased free tryptophan levels by sixfold in transgenic soybean leaves and twofold in seeds [79].



Biotechnology and Nutritional Improvement of Crops.

Figure 2

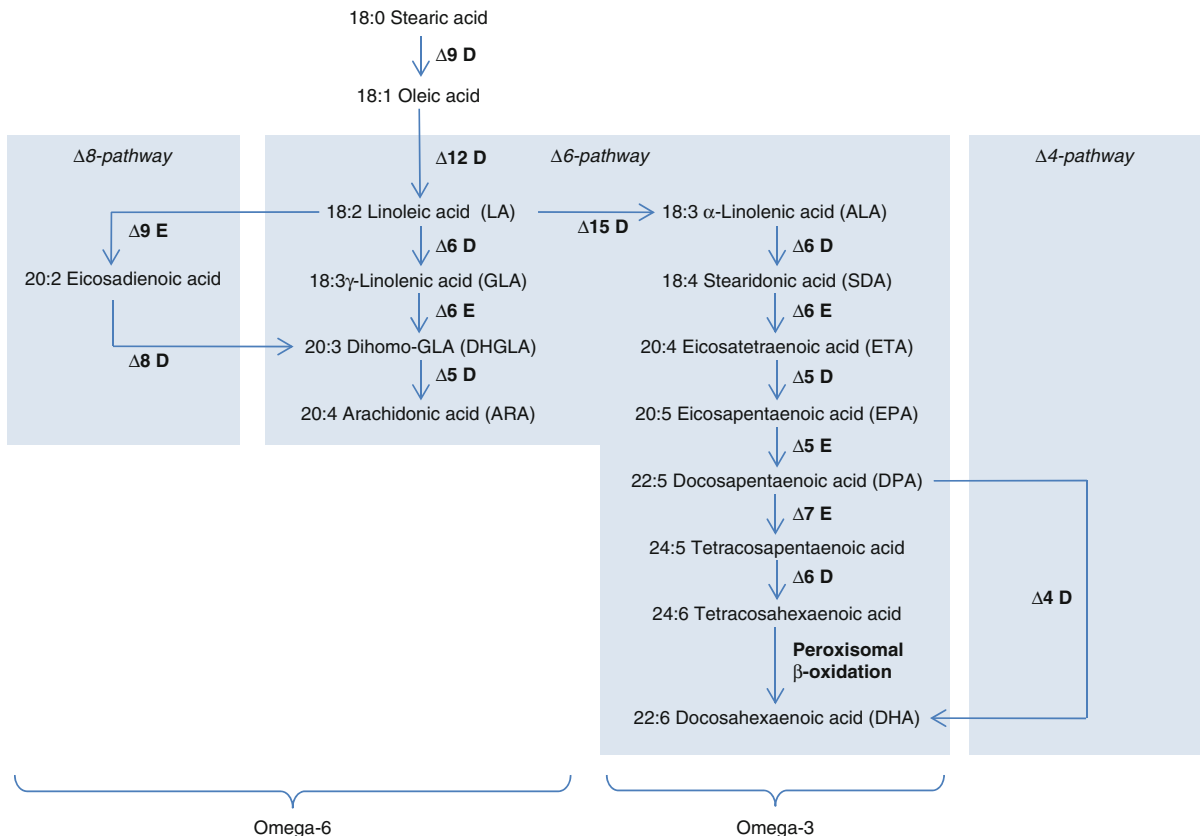
Lysine catabolism in plants, showing the production of three glutamate molecules for every molecule of lysine [63]. Enzyme abbreviations: LKR, lysine-ketoglutarate reductase; SDH, saccharopine dehydrogenase. Multiple arrows indicate several unspecified reactions

Tabé et al. [80] have recently shown that cysteine levels can be increased by up to 26-fold in developing lupin seeds by expressing a feedback-insensitive serine acetyltransferase (SAT). The levels of glutathione were also higher in developing seeds, but methionine levels were unaffected. Interestingly, the overall levels of cysteine and methionine in mature seeds did not change, suggesting feedback to counter the accumulation of cysteine later in development. The above strategy was also combined with the overexpression of a seed storage protein by crossing transgenic lines expressing the SAT enzyme with those expressing a sunflower albumin gene. Again, this resulted in higher levels of cysteine during development but no

change in the amount of methionine; there was no significant change in either amino acid in mature seeds [80].

Increasing the Availability of Essential Fatty Acids

Polyunsaturated fatty acids (PUFAs) are synthesized from saturated fats through an alternating sequence of desaturation and elongation reactions, each requiring a different class of enzymes (Fig. 3). Humans are unable to synthesize PUFAs because they lack the necessary $\Delta 12$ and $\Delta 16$ desaturases to convert oleic acid into α -linolenic acid (omega-3) and linoleic acid (omega-6). However, they do possess $\Delta 6$ and $\Delta 5$



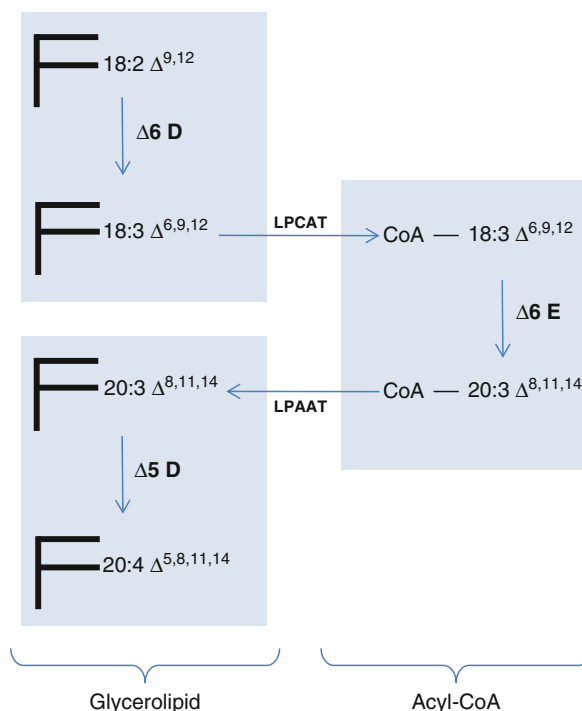
Biotechnology and Nutritional Improvement of Crops. Figure 3

Overview of very-long-chain polyunsaturated fatty acid synthesis focusing on the strategies that have been used in transgenic plants either by enhancing the standard $\Delta 6$ -pathway or importing enzymes from the alternative $\Delta 8$ -pathway and microbial $\Delta 4$ -pathway [82]. Enzymes identified by “D” and “E” are desaturases and elongases, respectively. Humans lack the $\Delta 12$ desaturase that converts oleic acid into linoleic acid

desaturases, so if adequate amounts of α -linolenic acid and linoleic acid can be sourced in the diet they can be converted into longer-chain molecules in the liver, yielding the very-long-chain (VLC) PUFAs eicosapentaenoic acid (EPA), docosahexaenoic acid (DHA), and arachidonic acid (ARA) [81]. Even so, this is a slow process because the $\Delta 6$ and $\Delta 5$ desaturases are inefficient, and these molecules can become limiting. Strategies to increase the availability of essential fatty acids in plants therefore not only concentrate on the accumulation of α -linolenic acid and linoleic acid but also on the VLC-PUFAs EPA, DHA, and ARA.

As shown in Fig. 3, the synthesis of EPA and ARA requires three enzyme activities: $\Delta 6$ -desaturase, $\Delta 6$ -elongase, and $\Delta 5$ -desaturase; DHA synthesis requires an additional β -oxidation step which occurs in peroxisomes [82]. The elongation steps require an acyl-CoA substrate, whereas the desaturations require the presence of phosphatidylcholine. The switching of fatty acids between the phosphatidylcholine and CoA pools is facilitated by acyltransferases and these are often the limiting step in VLC-PUFA synthesis [83] (Fig. 4). However, this bottleneck can be alleviated using the alternative $\Delta 8$ -pathway, in which the elongation and saturation steps are realized by a $\Delta 9$ -elongase, $\Delta 8$ -desaturase, and $\Delta 5$ -desaturase [84] (Fig. 3). This pathway is more efficient for ARA and EPA synthesis because there is less reliance on acyl exchange [82].

Four main strategies have been used to enhance VLC-PUFA biosynthesis in plants: expressing enzymes that increase the availability of precursors for α -linolenic acid and linoleic acid synthesis, enhancing the typical $\Delta 6$ -pathway, introducing the alternative $\Delta 8$ -pathway and importing the microbial $\Delta 4$ -pathway (Fig. 3). Thus far, enhancing the $\Delta 6$ -pathway has been most successful (Table 5), increasing the levels of ARA, EPA, and DHA by up to 25%, 15%, and 0.5%, respectively [85, 86]. However, Kinney et al. [87] showed that the levels of EPA and DHA could be increased by 19.5% and 3%, respectively, in soybean by enhancing the $\Delta 4$ - and $\Delta 6$ -pathways simultaneously, and Qi et al. [88] increased EPA levels to 3% and ARA levels by 6.6% in *Arabidopsis* by importing the $\Delta 8$ -pathway and removing the acyl exchange bottleneck.



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Figure 4

Fatty acid desaturation in plants requires glycerolipid substrates, whereas elongation requires acyl-CoA substrates. Successive desaturation and elongation steps therefore require substrates to be shuttled between phosphatidylcholine and coenzyme A (CoA) using enzymes known as acyltransferases. Enzymes identified by "D" and "E" are desaturases and elongases, respectively. Abbreviations: 18:2 $\Delta^{9,12}$, linoleic acid; 18:3 $\Delta^{6,9,12}$, γ -linolenic acid; 20:3 $\Delta^{8,11,14}$, dihomo- γ -linolenic acid; 20:4 $\Delta^{5,8,11,14}$, arachidonic acid; LPCAT, lysophosphatidylcholine acetyltransferase; LPAAT, lysophosphatidic acid acyltransferase

Increasing Vitamin Levels

Vitamin A In plants, carotenoids such as β -carotene (pro-vitamin A) are synthesized in the plastids via the methylerythritol-4-phosphate (MEP) pathway, also known as the non-MVA pathway. Initially, pyruvate and D-glyceraldehyde-3-phosphate are converted into 1-deoxy-D-xylulose-5-phosphate (DXP) by DXP synthase (DXS), and DXP is then converted into the isomeric C5 precursors isopentenyl diphosphate (IPP) and dimethylallyl pyrophosphate (DMAPP). Three

Biotechnology and Nutritional Improvement of Crops. Table 5 Transgenic plants with enhanced levels of essential fatty acids [82]

Species	Genes (source)	Promoters	% Fatty acids
<i>Arabidopsis</i> (<i>Arabidopsis thaliana</i>)	$\Delta 9$ -elongase (<i>Isochrysis galbana</i>)	Constitutive	ARA: 6.6
	$\Delta 8$ -desaturase (<i>Euglena gracilis</i>)	CaMV 35S	EPA: 3
	$\Delta 5$ -desaturase (<i>Mortierella alpine</i>)		
Arabidopsis	$\Delta 5/\Delta 6$ -desaturase (<i>Danio rerio</i>)	Seed-specific	ARA: 1.2
	$\Delta 6$ -elongase (<i>Caenorhabditis elegans</i>)	Napin	EPA: 2.5
	$\Delta 4$ -desaturase (<i>Pavlova salina</i>)		
	$\Delta 5$ -elongase (<i>P. salina</i>)		
Linseed (<i>Linum usitatissimum</i>)	$\Delta 6$ -desaturase (<i>Phaeodactylum tricornutum</i>)	Seed-specific	ARA: 1.5
	$\Delta 6$ -elongase (<i>Physcomitrella patens</i>)	USP	EPA: 1
Tobacco (<i>Nicotiana tabacum</i>)	$\Delta 5$ -desaturase (<i>P. tricornutum</i>)		ARA: 2
Soybean (<i>Glycine max</i>)	$\Delta 6$ -desaturase (<i>Saprolegnia diclina</i>)	Different seed-specific promoters	EPA: 19.5
	$\Delta 6$ -elongase (<i>M. alpina</i>)		ARA: 5.3
	$\Delta 5$ -desaturase (<i>M. alpina</i>)		
	<i>Fad3</i> (<i>Arabidopsis</i>)		
	$\Delta 17$ -desaturase (<i>Saprolegnia diclina</i>)		
	$\Delta 4$ -desaturase (<i>Syzygium aggregatum</i>)		
	Elongase (<i>P. salina</i>)		
Mustard (<i>Brassica juncea</i>)	$\Delta 6$ -desaturase (<i>Pythium irregulare</i>)	Seed-specific	ARA: 25
	$\Delta 6$ -elongase (<i>P. patens</i>)	Napin	EPA: 15
	$\Delta 5$ -desaturase (<i>Thraustochytrium</i> sp.)		
	$\Delta 12$ -desaturase (<i>Calendula officinalis</i>)		
	Elongase (<i>Thraustochytrium</i> sp.)		
	$\omega 3$ -desaturase (<i>Phytophthora infestans</i>)		
<i>Marchantia polymorpha</i>	$\Delta 6$ -desaturase (<i>Marchantia polymorpha</i>)	Constitutive	ARA: 11.4 (3.6-fold)
	$\Delta 6$ -elongase (<i>M. polymorpha</i>)	CaMV35S	EPA: 12.1 (2-fold)
	$\Delta 5$ -desaturase (<i>M. polymorpha</i>)		
Tobacco	$\Delta 6$ -desaturase (<i>M. polymorpha</i>)	Constitutive modified CaMV35S	ARA: 13.4
	$\Delta 6$ -elongase (<i>M. polymorpha</i>)		EPA: 3.2
	$\Delta 5$ -desaturase (<i>M. polymorpha</i>)		
Soybean	$\Delta 6$ -desaturase (<i>M. polymorpha</i>)	Seed-specific α' -subunit of β -conglycin	ARA: 3
	$\Delta 6$ -elongase (<i>M. polymorpha</i>)		EPA: 0.3
	$\Delta 5$ -desaturase (<i>M. polymorpha</i>)		

Source: Data updated from [82]

molecules of IPP condense with one molecule of DMAPP to form the C20 precursor geranylgeranyl diphosphate (GGPP), which is used for the synthesis of carotenoids, tocopherols, chlorophylls, plastoquinones, and gibberellins [89]. The first committed reaction in carotenoid biosynthesis is the conversion of GGPP to phytoene by phytoene synthase (PSY). In plants, phytoene then undergoes four desaturation steps catalyzed by phytoene desaturase (PDS) and ζ -carotene desaturase (ZDS) to generate the first colored carotene, *cis*-lycopene, which is converted to all-*trans*-lycopene by carotene isomerase (CRTISO) [90]. Lycopene is the substrate for two different enzymes – lycopene β -cyclase (LYCB), which adds β -ionone rings to both ends generating β -carotene; and lycopene ϵ -cyclase (LYCE), which adds an ϵ -ionone ring to one end, the other being cyclized by LYCB to generate α -carotene [90]. Both molecules can be hydroxylated to produce xanthophylls such as lutein, zeaxanthin, and violaxanthin (Fig. 5) although these do not have pro-vitamin A activity [90].

The amount of β -carotene produced by plants can be enhanced by increasing the availability of carotenoid precursors, by expressing enzymes in the common part of the pathway (between GGPP and lycopene), by biasing the pathway toward the β -branch through the expression of LYCB at the expense of LYCE, or by increasing the storage capacity for carotenoids (Table 6) [90].

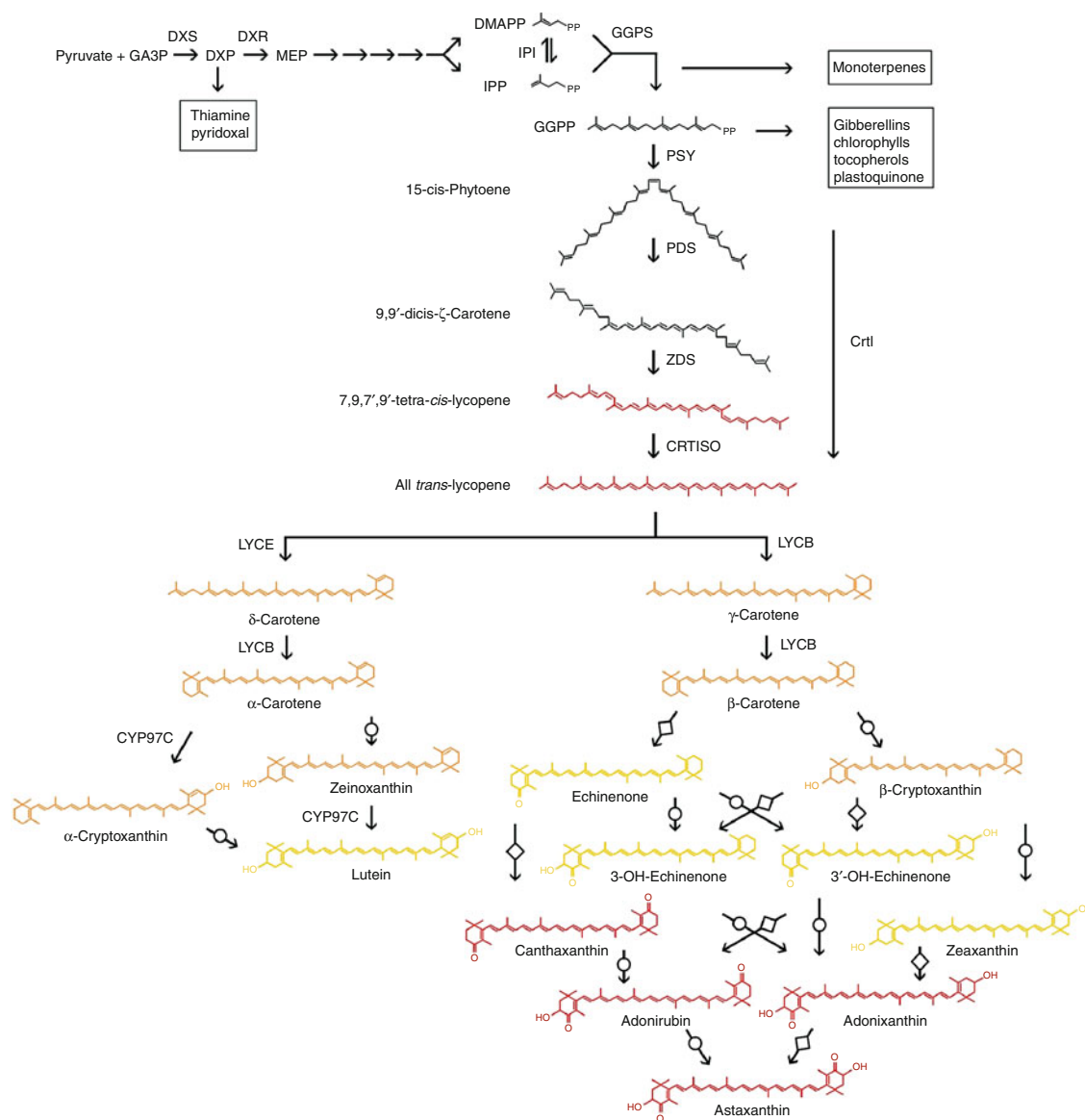
The first approach has been successful in producing plants that synthesize high levels of GGPP, but because this is used in several pathways not all of the flux is directed toward carotenoid synthesis. For example, the overexpression of DXP synthase in tomato and potato increased the total carotenoid content by up to 1.6-fold compared to wild type, but the levels of tocopherols and plastoquinones were also affected [91].

The expression of enzymes in the committed part of carotenoid pathway is a more targeted approach, and is particularly necessary in cereal grains where the pathway is blocked at the first committed step. In rice endosperm, the carotenoid pathway terminates at GGPP because there is very limited PSY activity. “Golden Rice” is a transgenic variety expressing daffodil PSY and LYCB as well as the multifunctional bacterial enzyme CrtI, which carries out all the desaturation steps between phytoene and lycopene. The β -carotene

content of the original Golden Rice was 1.6 $\mu\text{g/g DW}$ [92], but the replacement of daffodil PSY with the more active corn enzyme resulted in Golden Rice 2, in which the β -carotene levels reached 31 $\mu\text{g/g DW}$ [93]. Similar results have been achieved in corn endosperm. For example, Aluru et al. [94] expressed the bacterial enzymes CrtB (PSY) and CrtI under the control of an enhanced seed-specific promoter, increasing the total carotenoid level to 33.6 $\mu\text{g/g DW}$ and the β -carotene level to 9.8 $\mu\text{g/g DW}$. More recently, Zhu et al. [95] used a combinatorial transformation strategy to introduce up to five carotenogenic transgenes into corn, with the best-performing line (Ph-3, expressing PSY and CrtI), producing over 60 $\mu\text{g/g DW}$ of β -carotene. Another recent breakthrough in this area was the creation of transgenic corn plants transformed with four genes enabling the simultaneous modulation of three metabolic pathways [96]. As above, the carotenoid pathway was engineered with the genes encoding PSY and CrtI, resulting in a 169-fold increase in β -carotene levels to 57 $\mu\text{g/g DW}$. These combinatorial and stacked transgene approaches are discussed later in detail.

Similar progress has been made in the brassicas. The expression of bacterial CrtB (PSY) in canola resulted in a 50-fold increase in total carotene levels compared to wild-type seeds (1,617 $\mu\text{g/g fresh weight (FW)}$), with a β -carotene content of 949 $\mu\text{g/g FW}$ [97]. Ravanello et al. [98] achieved 1,341 $\mu\text{g/g FW}$ total carotenoids with the same gene. The combined expression of CrtB (PSY) and CrtI boosted levels to 1,412 $\mu\text{g/g FW}$, but further addition of CrtY (LYCB) reduced total carotenoid levels to 1,229 $\mu\text{g/g FW}$ although it increased the relative amount of β -carotene to 846 $\mu\text{g/g FW}$. Recently, Fujisawa et al. [99] introduced seven bacterial transgenes into canola encoding the enzymes isopentenyl pyrophosphate isomerase (which interconverts IPP and DMAPP), CrtE (GGPP synthase), CrtB (PSY), CrtI (carotene desaturase), CrtY (LYCB), and two additional enzymes (CrtZ and CrtW) that catalyze downstream steps converting β -carotene into ketocarotenoids. Although this resulted in the production of several ketocarotenoids, the predominant carotenoid was still β -carotene, which accumulated to 214.2 $\mu\text{g/g FW}$, 1,074-fold higher than in wild-type seeds.

Diretto et al. [100, 101] expressed CrtB, CrtI, and CrtY in potato tubers, increasing total carotenoid levels to 114 $\mu\text{g/g DW}$ and β -carotene levels to 47 $\mu\text{g/g DW}$.



Biotechnology and Nutritional Improvement of Crops. Figure 5

The extended carotenoid biosynthetic pathway in plants [171]. The precursor for the first committed step in the pathway is GGPP (geranylgeranyl pyrophosphate), which is converted into phytoene by phytoene synthase (PSY, CrtB). GGPP is formed by the condensation of IPP (isopentenyl pyrophosphate) and DMAPP (dimethylallyl pyrophosphate), which are derived predominantly from the plastidial MEP (methylerythritol 4-phosphate) pathway as shown in the upper part of the figure. The pathway is linear until lycopene, involving three steps catalyzed by separate enzymes in plants but by the single, multifunctional enzyme CrtI in bacteria. Lycopene is the branch point for the α - and β -carotene pathways, which usually end at lutein and zeaxanthin, respectively, through the expression of β -carotene hydroxylases (arrows with circles). An elaborated ketocarotenoid pathway can be introduced by expressing β -carotene ketolases (arrows with diamonds) since these compete for substrates with β -carotene hydroxylases and generate diverse products. Other abbreviations: GA3P, glyceraldehyde 3-phosphate; DXP, 1-deoxy-D-xylulose 5-phosphate; DXS, DXP synthase; DXR, DXP reductoisomerase; IPI, IPP isomerase; GGPPS, GGPP synthase; PDS, phytoene desaturase; ZDS, ζ -carotene desaturase; CRTISO, carotenoid isomerase; LYCB, lycopene β -cyclase; LYCE, lycopene ϵ -cyclase; HydE, carotene ϵ -hydroxylase

Biotechnology and Nutritional Improvement of Crops. Table 6 Transgenic plants with enhanced carotenoid levels [171]

Species	Genes (source)	Promoters	Carotenoid levels in transgenic plants
Rice (<i>Oryza sativa</i>)	<i>psy1</i> (daffodil; <i>Narcissus pseudonarcissus</i>)	CaMV35S (constitutive)	0.3 µg/g dry weight (DW) phytoene in seeds
		Gt1 (seed specific)	0.74 µg/g DW phytoene in seeds
	<i>psy1</i> and <i>lycb</i> (daffodil)	Gt1 (<i>psy1</i> and <i>lycb</i>) and CaMV35S (<i>crtl</i>)	1.6 µg/g DW total carotenoids in endosperm
	<i>crtl</i> (<i>Pantoea ananatis</i>)		
	<i>psy1</i> (corn)	Gt1	37 µg/g DW total carotenoids in seeds
	<i>crtl</i> (<i>P. ananatis</i>)		
Canola (<i>Brassica napus</i>)	<i>crtB</i> (<i>P. ananatis</i>)	Napin (seed specific)	1,617 µg/g fresh weight (FW) total carotenoids in seeds (50-fold)
	<i>crtB</i> (<i>P. ananatis</i>)	Napin	1,341 µg/g FW total carotenoids in seeds
	<i>crtE</i> and <i>crtB</i> (<i>P. ananatis</i>)		1,023 µg/g FW total carotenoids in seeds
	<i>crtB</i> (<i>P. ananatis</i>)		1,412 µg/g FW total carotenoids in seeds
	<i>crtl</i> (<i>P. ananatis</i>)		935 µg/g FW total carotenoids in seeds
	<i>crtB</i> and <i>crtY</i> (<i>P. ananatis</i>)		985 µg/g FW total carotenoids in seeds
	<i>crtB</i> and β -cyclase (<i>B. napus</i>)		1,229 µg/g FW total carotenoids in seeds
	<i>crtB</i> and <i>crtY</i> (<i>P. ananatis</i>)		412–657 µg/g FW total carotenoids in seeds (30-fold)
	<i>crtl</i> (<i>P. ananatis</i>)		60–190 µg/g FW total ketocarotenoids in seeds
	<i>idi</i> , <i>crtE</i> , <i>crtB</i> , <i>crtl</i> , and <i>crtY</i> (<i>P. ananatis</i>)	CaMV35S, napin and Arabidopsis <i>FAE1</i> (seed specific)	60–190 µg/g FW total ketocarotenoids in seeds
	<i>crtZ</i> , <i>crtW</i> (<i>Brevundimonas</i> sp.)		

Biotechnology and Nutritional Improvement of Crops. Table 6 (Continued)

Species	Genes (source)	Promoters	Carotenoid levels in transgenic plants
Tomato (<i>Solanum lycopersicum</i>)	<i>psy1</i> (tomato)	CaMV35S	3,615 µg/g DW total carotenoids in vegetative tissue (1.14-fold)
	<i>psy1</i> (tomato)	CaMV35S	2,276.7 µg/g DW total carotenoids in fruit (1.25-fold)
			819 µg/g DW β-carotene in fruit (1.4-fold)
	<i>crtI</i> (<i>P. ananatis</i>)	CaMV35S	520 µg/g DW (1.9-fold) β-carotene in fruit
	<i>lycb</i> (Arabidopsis) <i>chyb</i> (pepper; <i>Capsicum annuum</i>)	pds	63 µg/g FW β-carotene in fruit (12-fold)
	<i>crtB</i> (<i>P. ananatis</i>)	Polygalacturonase (fruit specific)	825 µg/g DW β-carotene in ripe fruit (2.5-fold)
	<i>dxs</i> (<i>Escherichia coli</i>)	Fibrillin	7,200 µg/g DW total carotenoids in fruit (1.6-fold)
	<i>det-1</i> (tomato, antisense)	P119, 2A11, and TFM7 (fruit specific)	130 µg/g DW β-carotene (8-fold) in red-ripe fruit (assuming a water content of 90%)
	<i>CRY2</i> (tomato)	CaMV35S	1,490 µg/g DW total carotenoids ripe fruit pericarps (1.7-fold)
			101 µg/g DW β-carotene ripe fruit pericarps (1.3-fold)
	<i>chrd</i> (cucumber; <i>Cucumis sativus</i>)	CaMV35S	Reduced carotenoid levels in flower
	<i>crtY</i> (<i>P. ananatis</i>)	aptI	286 µg/g DW β-carotene in fruit (4-fold)
	<i>Fibrillin</i> (pepper)	Fibrillin	150 pg/g FW β-carotene in fruit
	<i>lycb</i> (Arabidopsis)	pds (fruit specific)	546 µg/g DW FW total carotenoids in fruit (7-fold) (assuming a water content of 90%)
	<i>lycb</i> (tomato)	CaMV35S	2,050 µg/g DW total carotenoids in fruit (31.7-fold) (assuming a water content of 90%)
	<i>lycb</i> (daffodil)	Ribosomal RNA	950 µg/g DW β-carotene in fruit

Biotechnology and Nutritional Improvement of Crops. Table 6 (Continued)

Species	Genes (source)	Promoters	Carotenoid levels in transgenic plants
Potato (<i>Solanum tuberosum</i>)	ZEP (Arabidopsis)	GBSS (tuber specific)	60.8 µg/g DW total carotenoids in tubers (5.7-fold)
	crtB (<i>P. ananatis</i>)	Patatin (tuber specific)	35 µg/g DW total carotenoids in tubers (6.3-fold)
			11 µg/g DW β-carotene in tubers (19-fold)
	lyce (potato, antisense)	Patatin	12.27 µg/g DW total carotenoids in tubers (2.5-fold)
			0.043 µg/g DW β-carotene in tubers (14-fold)
	crtO (<i>Synechocystis</i> sp.)	CaMV35S	39.76 µg/g DW total carotenoids in tubers
			ketocarotenoids represented 10–12% of total carotenoids in tubers
	dxs (<i>E. coli</i>)	Patatin	7 µg/g DW total carotenoids in tubers (2-fold)
	crtB (<i>P. ananatis</i>) bkt1 (<i>Haematococcus pluvialis</i>)	Patatin	5.2 µg/g DW total carotenoids in tubers
			1.1 µg/g DW total ketocarotenoids in tubers
	bkt1 (<i>H. pluvialis</i>)	Patatin	30.4 µg/g DW total carotenoids in tubers
			19.8 µg/g DW total ketocarotenoids in tubers
	or (cauliflower; <i>Brassica oleracea</i> var <i>botrytis</i>)	GBSS	25 µg/g DW total carotenoids (6-fold) in tubers
	or (cauliflower)	GBSS	31 µg/g DW total carotenoids in tubers (5.7-fold)
	crtB, crtI, and crtY (<i>P. ananatis</i>)	Patatin	114 µg/g DW total carotenoids in tubers (20-fold)
			47 µg/g DW β-carotene in tubers (3,600-fold)
	bch (potato, antisense)	Patatin	21.7 µg/g DW total carotenoids in tubers (4.5-fold)
			0.085 µg/g DW β-carotene in tubers (38-fold)
	bch (potato, antisense)	GBSS and CaMV35S	3.31 µg/g DW β-carotene in tubers

Biotechnology and Nutritional Improvement of Crops. Table 6 (Continued)

Species	Genes (source)	Promoters	Carotenoid levels in transgenic plants
Corn (<i>Zea mays</i>)	<i>psy1</i> (corn)	Wheat LMW glutelin, barley (<i>Hordeum vulgare</i>) D-hordein, corn γ -zein, rice prolamin (all endosperm-specific)	146.7 $\mu\text{g/g}$ DW total carotenoids in seeds
	<i>crtI</i> (<i>P. ananatis</i>)		35.85 $\mu\text{g/g}$ DW total ketocarotenoids in seeds
	<i>crtW</i> (<i>Paracoccus</i> spp.)		
	<i>lycb</i> (<i>Gentiana lutea</i>)		
	<i>crtB</i> and <i>crtI</i> (<i>P. ananatis</i>)	super γ -zein	33.6 $\mu\text{g/g}$ DW total carotenoids in seeds (34-fold)
	<i>psy1</i> (corn)	Wheat LMW glutelin and barley D-hordein	163.2 $\mu\text{g/g}$ DW total carotenoids in seeds (112-fold)
	<i>crtI</i> (<i>P. ananatis</i>)		59.32 $\mu\text{g/g}$ DW β -carotene in seeds (169-fold)
Lotus japonicus	<i>crtW</i> (<i>Agrobacterium aurantiacum</i>)	CaMV35S	387 $\mu\text{g/g}$ FW total carotenoids in flower petals (1.5-fold)
			89.9 $\mu\text{g/g}$ FW total ketocarotenoids in flower petals (2.2-fold)
Carrot (<i>Daucus carota</i>)	<i>bkt1</i> (<i>H. pluvialis</i>)	CaMV35S and <i>Agrobacterium rhizogenes</i> rolD (root specific)	345.5 $\mu\text{g/g}$ FW total carotenoids in root
	<i>chyB</i> (<i>Arabidopsis</i>)		2,400 $\mu\text{g/g}$ root DW novel ketocarotenoids
	<i>psy</i> (<i>Arabidopsis</i>)	CaMV35S	858.4 $\mu\text{g/g}$ DW total carotenoids in roots
Tobacco (<i>Nicotiana tabacum</i>)	<i>crtW</i> and <i>crtZ</i> (<i>Paracoccus</i> sp.)	CaMV35S	1,275 $\mu\text{g/g}$ DW total carotenoids in leaves
			64 $\mu\text{g/g}$ FW total ketocarotenoids in leaves
	<i>crtO</i> (<i>Synechocystis</i> sp.) <i>crtZ</i> (<i>P. ananatis</i>)	CaMV35S	839 $\mu\text{g/g}$ DW total carotenoids in leaves (2.5-fold)
			342.4 $\mu\text{g/g}$ DW total ketocarotenoid in leaves
	<i>crtO</i> (<i>Synechocystis</i> sp.)	CaMV35S	429 $\mu\text{g/g}$ DW total carotenoids in leaves
			156.1 $\mu\text{g/g}$ DW total ketocarotenoid in leaves
	<i>crtW</i> and <i>crtZ</i> (<i>Brevundimonas</i> sp.)	<i>rrn</i>	7,380 $\mu\text{g/g}$ FW total carotenoids in leaves (2.1-fold)
			7,290 $\mu\text{g/g}$ FW total ketocarotenoids in leaves
Wheat (<i>Triticum aestivum</i>)	<i>psy1</i> (corn) <i>crtI</i> (<i>P. ananatis</i>)	CaMV35S and 1D \times 5 (constitutive)	4.96 $\mu\text{g/g}$ DW in seeds

Biotechnology and Nutritional Improvement of Crops. Table 6 (Continued)

Species	Genes (source)	Promoters	Carotenoid levels in transgenic plants
Arabidopsis (<i>Arabidopsis thaliana</i>)	<i>bkt1</i> (<i>H. pluvialis</i>)	Napin	4-keto-lutein, canthaxanthin, and adonirubin seeds up to 13-fold
	<i>bch</i> (Arabidopsis)	CaMV35S	2,274.8 nmol/g DW total carotenoids
	<i>psy</i> (Arabidopsis)	Napin	260 µg/g FW β-carotene in seeds
	<i>psy</i> (Arabidopsis)	CaMV35S	1,600 µg/g DW (10-fold) in seed-derived calli and 500 µg/g DW (100-fold) of total carotenoids in roots
	<i>chyB</i> (Arabidopsis)	CaMV35S	285 mmol/chl a(mol) violaxanthin (2-fold)
			728 mmol/chl a(mol) of total carotenoid
	<i>AtB1</i> (Arabidopsis)	CaMV35S	38.2 µg/g β-carotene leaf tissue
	<i>CYP97A3</i> (Arabidopsis)	CaMV35S	41.7 µg/g β-carotene leaf tissue
	<i>CYP97B3</i> (Arabidopsis)	CaMV35S	36.7 µg/g β-carotene leaf tissue
	<i>CYP97C1</i> (Arabidopsis)	CaMV35S	41.3 µg/g β-carotene leaf tissue

Source: Data updated from [171]

They also silenced the endogenous *lyce* and *bch* genes, thereby eliminating competition at the branch point between the α- and β-carotene pathways and preventing the further metabolism of β-carotene.

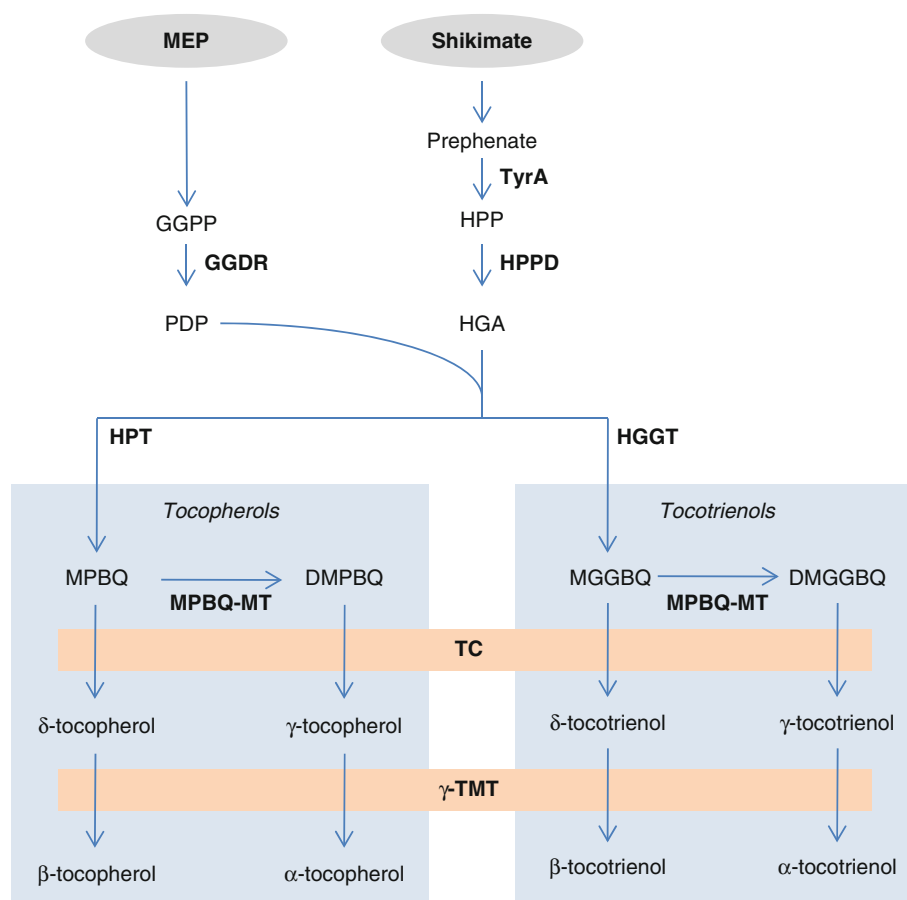
Ripening tomatoes accumulate low levels of β-carotene and in order to address this deficiency, several investigators have attempted to overexpress either the endogenous *lycb* gene or equivalent heterologous genes [102–106]. D'Ambrosio et al. [103] have been the most successful with this approach, achieving a 32-fold increase in β-carotene levels and generating orange-colored tomato fruits. Another successful strategy was the suppression of the endogenous *DET1* gene, which regulates photomorphogenesis. The expression of a *det1* RNAi construct in tomato chromoplasts increased β-carotene levels eightfold to 130 µg/g DW [107].

An alternative strategy to achieve β-carotene accumulation in plants is to modify the storage capacity of chromoplasts, where β-carotene accumulates in

specialized lipoprotein-sequestering structures. A spontaneous mutation in the cauliflower *Orange* (*Or*) gene resulted in deep orange cauliflower heads associated with the hyperaccumulation of carotenoids in chromoplasts [108, 109] and the mutant allele has been cloned and expressed in potato tubers, where it increased the level of β-carotene tenfold and turned the tuber flesh orange [110].

Vitamin E Vitamin E is a collection of four tocopherols and four tocotrienols (each as α, β, γ, and δ derivatives), collectively known as tocochromanols [111]. All eight isomers can be absorbed equally efficiently during digestion but the hepatic α-tocopherol transfer protein (α-TTP) shows preferential retention of α-tocopherol, making it the most important form in terms of vitamin E activity in the human body [111].

Tocochromanol biosynthesis in higher plants (Fig. 6) occurs in the plastids and requires precursors from the cytosolic shikimate pathway and the plastidial



Biotechnology and Nutritional Improvement of Crops. Figure 6

Vitamin E synthesis in plants [111]. The pathway involves the prenylation of homogentisic acid (HGA), derived from the shikimate pathway, with phytyldiphosphate (PDP), derived from the methylerythritol phosphate (MEP) pathway. Prenylation may be carried out by two different enzymes – HPT (homogentisate phytyltransferase) or HGGT (homogentisate geranylgeranyl transferase) – to generate alternative intermediates that give rise to the tocopherol and tocotrienol branches of the pathway, respectively. These intermediates are substrates for the same three enzymes, yielding eight different products. Additional substrate abbreviations: GGPP, geranylgeranyl pyrophosphate; HPP: *p*-hydroxyphenylpyruvic acid; MPBQ, 2-methyl-6-phytylbenzoquinol; DMPBQ, 2,3-dimethyl-5-phytylbenzoquinol; MGGBQ, 2-methyl-6-geranylgeranylplastoquinol; DMGGBQ, 2,3-dimethyl-5-geranylgeranylplastoquinol. Additional enzyme abbreviations: GGDR, geranylgeranyl diphosphate reductase; HPPD, HPP dioxygenase; MPBQ-MT: MPBQ methyltransferase; TC, tocopherol cyclase; γ -TMT: γ -tocopherol methyltransferase

MEP pathway [111]. The tocochromanol head group is derived from the shikimate pathway, and this involves the conversion of *p*-hydroxyphenylpyruvic acid (HPP) to homogentisic acid (HGA), by HPP dioxygenase (HPPD); the MEP pathway contributes the side chain [111]. The first committed step in tocochromanol biosynthesis is the prenylation of HGA. There are two enzymes that carry out this reaction. If prenylation is

carried out by homogentisate phytyltransferase (HPT), the product is 2-methyl-6-phytylplastoquinol (MPBQ), which leads to the synthesis of tocopherols. Alternatively, HGA can be prenylated by homogentisate geranylgeranyl transferase (HGGT), producing 2-methyl-6-geranylgeranylplastoquinol (MGGBQ), which leads to the synthesis of tocotrienols [111].

The eight isomers form through a complex series of reactions involving enzymes with multiple substrates at each stage. Both MPBQ and MGGBQ are substrates for tocopherol cyclase (TC), leading to the production of δ -tocopherol and δ -tocotrienol, respectively. They are also substrates for the enzyme MPBQ methyltransferase (MPBQ-MT), which adds a second methyl group to form 2,3-dimethyl-5-phytyl-1,4-benzoquinone (DMPBQ) and 2,3-dimethyl-5-geranylgeranyl-1,4-benzoquinone (DMGGBQ), respectively. These methylated derivatives are also substrates for TC, leading to the production of γ -tocopherol and γ -tocotrienol, respectively. Finally, all four of these products (the δ - and γ -tocopherols, and the δ - and γ -tocotrienols) can be methylated by γ -tocopherol methyltransferase (γ -TMT) to produce their β - and α - counterparts [111].

Plants can be engineered to accumulate higher levels of vitamin E by overexpressing the genes involved in tocochromanol synthesis, and this can be achieved either by increasing the total tocochromanol content or skewing tocochromanol synthesis toward the more potent vitamers, particularly α -tocopherol (Table 7). In the first approach, the overexpression of HPT increased tocopherol levels by up to 1.6-fold in the seeds and 4.4-fold in the leaves of transgenic

Arabidopsis plants [112]. The overexpression of HPPD increased tocotrienol levels tenfold in Arabidopsis leaves [113], twofold in tobacco leaves, and 1.5-fold in tobacco seeds [114]. In the second approach, the expression of Arabidopsis γ -TMT in lettuce increased the α/γ tocopherol ratio but had no effect on the total tocopherol content [115]. However, by crossing the lines expressing HPT and γ -TMT, both the total tocopherol content and the α/γ tocopherol ratio were increased [115]. In canola, total tocochromanol levels have been doubled by expressing genes encoding HPT, HPPD, and TC [116].

The impact of HPPD expression can be enhanced by the simultaneous expression of TyrA, the enzyme responsible for the synthesis of HPP from prephenate (Fig. 6). TyrA expression has little effect on its own, but when combined with HPPD in tobacco, tocochromanol levels in the leaves increased eightfold [117]. Similar results have been achieved in Arabidopsis, canola, and soybean seeds using the same combination of genes, although the total tocochromanol content increased only 2–2.5-fold in these cases [118]. The expression of HPT, HPPD, and TyrA increased the tocochromanol content of seeds fivefold, and the further addition of geranylgeranyldiphosphate reductase (GGDR), which provides

Biotechnology and Nutritional Improvement of Crops. Table 7 Transgenic plants with enhanced tocochromanol levels [111]

Species	Genes (source)	Promoters	Tocochromanol levels in transgenic plants
Tobacco (<i>Nicotiana tabacum</i>)	<i>hppd</i> (barley; <i>Hordeum vulgare</i>)	CaMV 35S	50 $\mu\text{g/g}$ DW in seeds (1.5–2-fold)
	<i>tyrA</i> (<i>Erwinia uredovora</i>)	Arabidopsis histone gene H4748	67 $\mu\text{g/g}$ DW in leaf (1.3-fold)
	<i>tyrA</i> (<i>E. uredovora</i>), <i>hppd</i> (Arabidopsis)		14.3 $\mu\text{g/g}$ DW of α -tocotrienols
			551 $\mu\text{g/g}$ DW in leaf (10-fold)
Corn (<i>Zea mays</i>)	<i>hggt</i> (barley)	Embryo-specific	>800 nmol/g DW in seeds (6-fold)
	<i>hppd</i> and <i>vte3</i> (Arabidopsis)	CaMV 35S	9.5 $\mu\text{g/g}$ DW (3-fold)
Lettuce (<i>Lactuca sativa</i>)	<i>vte4</i> (Arabidopsis)	CaMV 35S	Improved α/γ -tocopherol ratio up to 0.4–544 as compared to α/γ ratio in wild type, which is 0.6–1.2
Mustard (<i>Brassica juncea</i>)	<i>vte4</i> (Arabidopsis)	CaMV 35S	62.29 $\mu\text{g/g}$ of α -tocopherol levels in seeds (6-fold)

Biotechnology and Nutritional Improvement of Crops. Table 7 (Continued)

Species	Genes (source)	Promoters	Tocochromanol levels in transgenic plants
Canola (<i>Brassica napus</i>)	<i>hppd</i> (Arabidopsis)	DC3 Ω	819 μ g/g oil in seeds (1.2-fold)
	<i>hppd</i> , <i>hpt1</i> , <i>vte1</i> (Arabidopsis)	DC3 Ω (<i>hppd</i>), napin (<i>hpt1</i> , <i>vte1</i>)	1,850 μ g/g oil in seeds (2-fold)
	<i>tyrA</i> (<i>E. uredoovora</i>)	Lac	540 μ g/g of total tocochromanols in seeds (2.3-fold)
	<i>tyrA</i> (<i>E. uredoovora</i>), <i>hppd</i> , <i>hpt1</i> (Arabidopsis)	Lac	3.7-fold increase in seeds
	<i>vte1</i> (Arabidopsis)	Napin	1,018 μ g/g oil of total tocochromanols in seeds (20–50% increase)
	<i>vte1</i> (corn)	Napin	1,159 μ g/g oil of total tocochromanols in seeds
Soybean (<i>Glycine max</i>)	<i>tyrA</i> (<i>E. uredoovora</i>), <i>hppd</i> , <i>hpt1</i> and <i>ggh</i> (Arabidopsis)	Lac	4,806 μ g/g of total tocochromanols in seeds (15-fold)
	<i>vte3</i> (Arabidopsis)	7S α	The majority of the tocopherol accumulated as γ -tocopherol (75–85%) with increased α -tocopherol as well. By contrast, these seeds had very low levels of β - and δ -tocopherol, only 0.5–1.5% of total tocopherols
	<i>vte4</i> (Arabidopsis)	7S α	100% of α -tocopherols in seeds
	<i>vte3</i> and <i>vte4</i> (Arabidopsis)	7S α	8-fold increase in α -tocopherol in seeds
	<i>vte4</i> (<i>Perilla frutescens</i>)	Vicilin	390 nmol/g FW of α -tocopherol content in seeds (10.4-fold)
			52 nmol/g FW of β -tocopherol content in seed (14.9-fold)
Arabidopsis (<i>Arabidopsis thaliana</i>)	<i>vte4</i> (Arabidopsis)	DC3	328 μ g/g α -tocopherol in seeds (86-fold)
	<i>hppd</i> (Arabidopsis)	CaMV 35S, DC3	37% and 28% increase of tocopherol levels in leaf and seed respectively
	<i>hpt1</i> (Arabidopsis)	CaMV 35S	4.4-fold increase in total leaf tocopherol content (mainly α -tocopherols)
	<i>hpt1</i> (Arabidopsis)	Napin	2-fold increase of tocopherols in seed

Source: Data updated from [111]

the precursor phytyldiphosphate, increased the tocochromanol content by up to 15-fold [118].

The seed-specific expression of Arabidopsis MPBQ-MT and γ -TMT in soybean resulted in a complete conversion of β -, γ -, and δ -tocopherols to α -tocopherol, with a fivefold enhancement in the vitamin E activity of soybean oil [119]. Similarly, Tavva et al. [120] achieved a 10.4-fold increase in α -tocopherol levels and a 14.9-fold increase in β -tocopherol levels in soybean seeds expressing *Perilla frutescens* γ -TMT.

Vitamin C Most vitamin C (ascorbic acid) in plants is synthesized through the L-galactose pathway [121], although other routes through galacturonic acid, L-glucose, and *myo*-inositol have been proposed [122]. Oxidation of ascorbic acid produces the short-lived radical monodehydroascorbate (MDHA), which is either converted to ascorbic acid by MDHA reductase (MDHAR) or undergoes spontaneous degradation into ascorbic acid and dehydroascorbate (DHA). DHA is then either recycled to ascorbic acid by dehydroascorbate reductase (DHAR), using



Plants of the genus *Actinidia* are particularly rich in ascorbic acid, so genes from the ascorbate biosynthesis pathway in *Actinidia* species have been expressed in model plants to ascertain if this can be used to boost ascorbate levels. Transgenic tobacco plants expressing *Actinidia chinensis* GDP-L-galactose guanyltrifosphate transferase contained threefold the normal levels of ascorbate in the leaves [126] whereas *Arabidopsis* plants expressing the equivalent enzyme from *Actinidia eriantha* contained 4.2-fold more ascorbate than normal. Expressing this enzyme in concert with GDP-L-mannose-3',5'-epimerase achieved a 12-fold increase in ascorbate revealing an important bottleneck in the L-galactose pathway [127].

Biotechnology and Nutritional Improvement of Crops. Table 8 Transgenic plants with enhanced ascorbate levels [122]

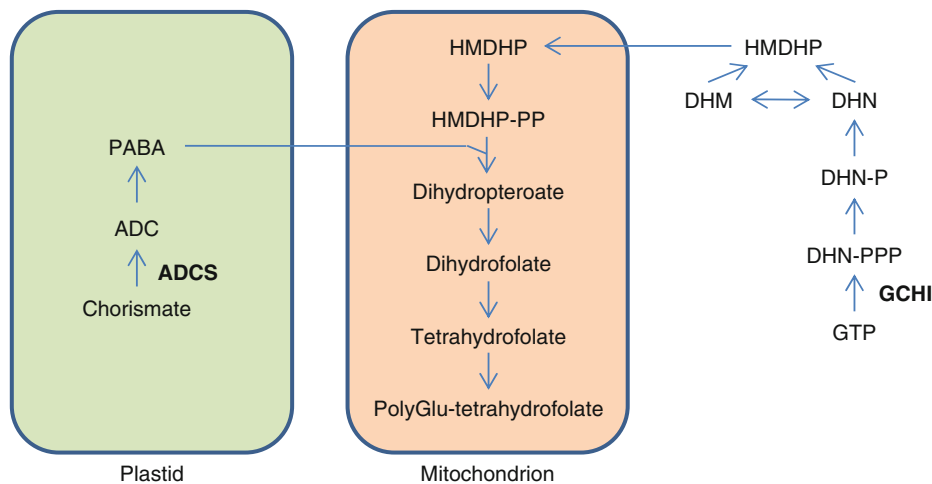
Species	Genes (source)	Promoters	Ascorbate levels in transgenic plants
Corn (<i>Zea mays</i>)	<i>dhar</i> (wheat; <i>Triticum aestivum</i>)	Corn Ubi-1 (constitutive)	~150 nmol/g FW in kernel (1.9-fold)
	<i>dhar</i> (rice; <i>Oryza sativa</i>)	Barley (<i>Hordeum vulgare</i>) D-hordein	607.2 nmol/g FW (6.1-fold)
Tomato (<i>Solanum lycopersicum</i>)	<i>mMDH</i>	CaMV 35S (constitutive)	(5–6-fold)
Lettuce (<i>Lactuca sativa</i>)	<i>GLOase</i> (rat; <i>Rattus norvegicus</i>)	CaMV 35S	430–580 nmol/g FW (4–7-fold)
Tobacco (<i>Nicotiana tabacum</i>)	<i>GLOase</i> (rat)	CaMV 35S	480 nmol/g FW (7-fold)
	<i>dhar</i> (wheat)	CaMV 35S	2,800 nmol/g FW (2.4-fold)
	<i>GalLDH</i> (tobacco)	CaMV 35S	(1.5–2-fold)
	<i>GMP</i> (<i>Malpighia glabra</i>)	MgGMP	800–1,000 nmol/g FW (2-fold)
	<i>GGT</i> (GDP-L-galactose D- mannose-1-phosphate guanyltransferase) (<i>Actinidia chinensis</i>)	CaMV 35S	1,000 µg/g FW (3-fold)
	<i>PMM</i> (<i>M. glabra</i>)	MgGMP	700 µg/g FW (2-fold)
Arabidopsis (<i>Arabidopsis thaliana</i>)	<i>GalUR</i> (strawberry; <i>Fragaria</i> × <i>ananassa</i>)	CaMV 35S	~600 nmol/g (3-fold)
	<i>miox4</i> (Arabidopsis)	CaMV 35S	~500 nmol/g FW (2–3-fold)
	<i>GGT</i> (GDP-L-galactose guanyltransferase) (<i>Actinidia eriantha</i>)	CaMV 35S	8.6–12-fold
	<i>GME</i> (GDP-L-mannose-3',5'-epimerase) (<i>A. eriantha</i>)	CaMV 35S	

Source: Data updated from [122]

Folate Folic acid is a tripartite molecule combining pterin, p-aminobenzoate (PABA), and one or more glutamate moieties. The three parts of the molecule are produced separately in different subcellular compartments (plastids, cytosol, and mitochondria) and then joined together. Pterin is formed from guanosine triphosphate (GTP) in the cytosol and PABA is formed from chorismate in the plastids. These moieties are then transported to the mitochondria, where they condense to form dihydropteroate and are converted to polyglutamates (Fig. 8). Metabolic engineering can be used to increase folate levels in plants but the

compartmentalization of the pathway adds a degree of complexity (Table 9).

Initial strategies involving modulation of individual branches of the pathway have been moderately successful. For example, expressing GTP cyclohydrolase 1 (GCH1) enhances the cytosolic (pterin) branch of the pathway and increases pterin levels, which ensures that the other two branches become rate limiting. In tomato, this approach doubled the normal levels of folate in the fruit [128]. Similar results were achieved by enhancing the PABA branch of the pathway by overexpressing aminodeoxychorismate synthase



B

Biotechnology and Nutritional Improvement of Crops. Figure 8

Synthesis of folate in plants [96]. Abbreviations: aminodeoxychorismate (ADC), GTP cyclohydrolase I (GCHI), ADC synthase (ADCS), DHN, dihydroneopterin; -P/-PP/-PPP, mono/di/triphosphate; DHM, dihydromonopterin; HMDHP, hydroxymethyldihydropterin

Biotechnology and Nutritional Improvement of Crops. Table 9 Transgenic plants with enhanced folate levels [172]

Species	Genes (source)	Promoters	Folate levels in transgenic plants
Tomato (<i>Solanum lycopersicum</i>)	<i>gtpchl</i> (mammalian)	Tomato E8	0.8–2.3 nmol/g FW (2-fold)
	<i>gtpchl</i> (mammalian) and <i>adcs</i> (Arabidopsis)	Tomato E8	8.4 µg/g DW (25-fold)
Corn (<i>Zea mays</i>)	<i>folE</i> (<i>Escherichia coli</i>)	Barley (<i>Hordeum vulgare</i>) D-hordein	1.94 µg/g DW (2-fold)
Arabidopsis (<i>Arabidopsis thaliana</i>)	<i>folE</i> (<i>E. coli</i>)	CaMV 35S	2.27–4.70 nmol/g FW (2–4-fold)
Rice (<i>Oryza sativa</i>)	<i>gtpchl</i> (Arabidopsis)	Rice endosperm-specific globulin (glb-1)	38.3 nmol/g (100-fold)
	<i>adcs</i> (Arabidopsis)		
Lettuce (<i>Lactuca sativa</i>)	<i>gtpchl</i> (chicken; <i>Gallus gallus</i>)	CaMV 35S	1.9 µg/g (5.4-fold)

Source: Data updated from [172]

(ADCS) [129]. Each of these experiments revealed the limitations of the other pathway branches, but by crossing the two transgenic lines, the enhanced pathways were combined resulting in complementation between them and the creation of transgenic tomato fruits containing 25-fold the normal levels of folate [129]. The strategy has been replicated in other crops with similarly impressive results: the expression of

Arabidopsis GCH1 and ADCS in rice endosperm, e.g., increased folate levels by up to 100-fold [130].

Pantothenate Although most work in the area of vitamin enhancement in plants has focused on vitamins A, B₉ (folate), C, and E, there have been a small number of studies addressing other vitamins. Fouad and Rathinasabapathi [131] expressed the *E. coli*

panD gene encoding L-aspartate- α -decarboxylase (ADC) in tobacco and increased the level of pantothenate (vitamin B₅) in the leaves by up to 4.1-fold. Similarly, Chakauya et al. [132] expressed the *E. coli panB* gene encoding ketopantoate hydroxymethyltransferase (KPHMT) in canola, increasing levels of pantothenate in leaves, flowers, siliques, and seeds by 1.5–2.5-fold compared with the wild type.

Increasing Mineral Levels

In contrast to the situation with vitamins and essential amino acids and fatty acids, the mineral content of plants cannot be increased by metabolic engineering because minerals are not synthesized de novo by plants; instead they are taken up from the environment. Therefore, increasing the mineral density of plants using biotechnology involves a different set of strategies, focusing on the introduction of genes that improve the efficiency of mineral extraction from the soil (through improved mobilization and/or improved uptake), improve the efficiency of transport from the roots to storage organs such as seeds and fruits, and increase the capacity of storage organs to store minerals in a form that is available in the diet and not toxic to the plant [23, 32]. In addition, these strategies can be supplemented with those seeking to reduce the abundance of antinutritional compounds such as phytate, which inhibits mineral absorption in the gut, and/or to increase the abundance of nutritional enhancer compounds such as inulin, which facilitate mineral absorption by slowing down the progress of food through the gut (Table 10).

Mineral Uptake and Transport The efficiency with which minerals are taken up from the soil depends on their accessibility, which in turn reflects their solubility and interactions with soil particles. Iron is present in the soil mainly as Fe³⁺, an insoluble form with the tendency to bind strongly to inert particles. Therefore, plants have evolved two distinct strategies to facilitate iron absorption (Fig. 9). Strategy I is used by non-graminaceous plants and involves acidifying the rhizosphere through the secretion of protons, reducing Fe³⁺ to Fe²⁺ using reductases and then absorbing the soluble Fe²⁺ using specific transporters. Strategy II is used by graminaceous plants and involves the direct

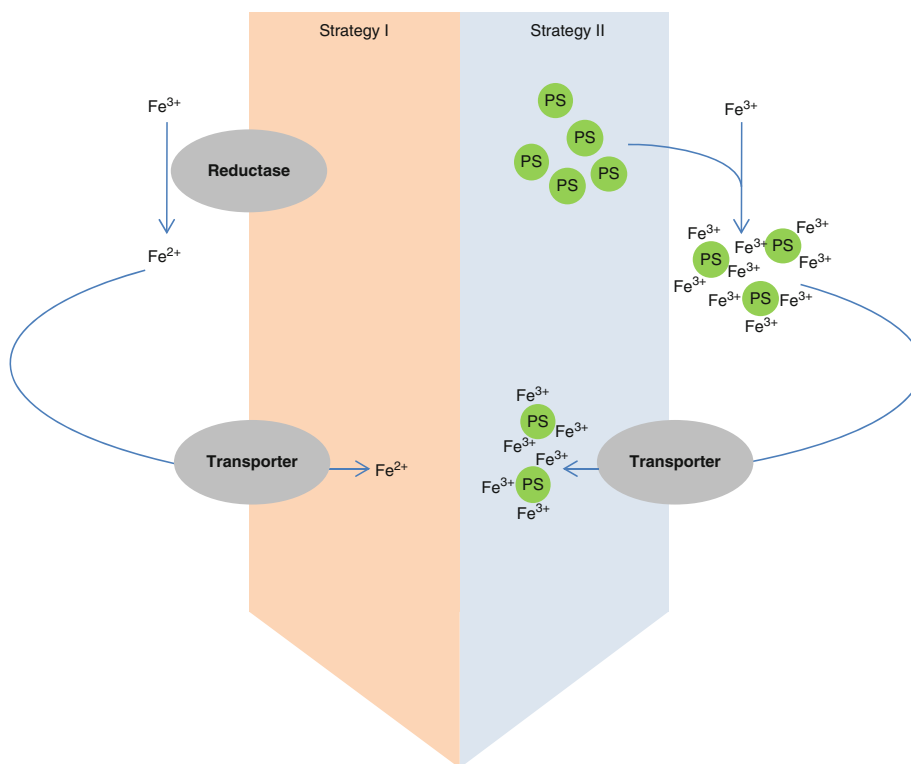
Biotechnology and Nutritional Improvement of Crops.

Table 10 Some examples of mineral nutritional enhancers and antinutrients in plant foods [37]

Nutritional enhancers	Major dietary source
β -Carotene (pro-vitamin A)	Green and orange vegetables
Certain amino acids (cysteine, lysine, etc.)	Animal meats
Certain organic acids (ascorbic acid, citrate, etc.)	Fresh fruit and vegetables
Hemoglobin	Animal meats
Inulin	Chicory, garlic, onion, wheat, artichoke
Long-chain fatty acids	Human breast milk
Antinutrients	Major dietary source
Phytic acid (phytate)	Whole legume seeds and cereal grains
Goitrogens	Brassicas and Alliums
Hemagglutinins	Most legumes and wheat
Oxalic acid (oxalate)	Different vegetables (spinaches, beet, linseed, oca)
Tannins and other polyphenolics	Tea, coffee, beans, sorghum

Source: Adapted from [37]

acquisition of Fe³⁺ by secreting chelating agents (phytosiderophores) into the rhizosphere, followed by adsorption of the chelated iron complexes. Specific root transporters are then required for the uptake of the soluble Fe³⁺-phytosiderophore complexes [133]. Zinc is present in soil as Zn²⁺ and can be directly absorbed in this form. Many of the genes required for zinc uptake, sequestration, and redistribution in plants have been identified [44] and it is thought that zinc-hyperaccumulating plants sequester large amounts of zinc in the vacuole, a strategy that confers zinc tolerance. However, Zn²⁺ can also form chelates with phytosiderophores, and the Zn²⁺-phytosiderophore complexes share the same channels as those used for iron chelates. Therefore, some strategies that have been developed to improve the uptake of iron also improve the uptake of zinc as a beneficial by-product, and vice



Biotechnology and Nutritional Improvement of Crops. Figure 9

Strategies for iron acquisition by plants [134]. Strategy I, as used by non-graminaceous plants, involves the acquisition of Fe^{2+} after reduction of Fe^{3+} in the rhizosphere by secreted reductases. Strategy II, as used by graminaceous plants, involves the secretion of phytosiderophores (PS) which chelate Fe^{3+} , allowing absorption of the chelated complexes

versa, although this depends on the genes involved [134]. Other minerals are taken up through specific transporters, e.g., plants take up selenium from the soil in the form of selenate (via sulfate transporters), selenite (via phosphate transporters), or as organic compounds (selenoproteins), and they take up calcium via specific $\text{Ca}^{2+}/\text{H}^{+}$ antiporters (CAX). Once inside the plant, minerals may also share transport mechanisms – e.g. Fe^{2+} , Zn^{2+} , and Ca^{2+} may all form complexes with nicotianamine for transport through the phloem to sink tissues.

In order to improve iron uptake from the soil, transgenic plants have been created expressing heterologous iron transporters, reductases, and enzymes involved in phytosiderophore biosynthesis (Table 11). For strategy I plants, such approaches have usually involved the expression of iron transport proteins, whereas for strategy II plants, iron accumulation can be enhanced by the production of higher levels of

phytosiderophores, with the anticipated collateral effects on zinc absorption [23]. In rice, e.g., iron and zinc uptake was improved by the expression of the barley *naat-A* and *naat-B* genes encoding nicotianamine aminotransferases, which are involved in phytosiderophore biosynthesis [135]. Similarly, the overexpression of barley nicotianamine synthase in tobacco doubled the iron and zinc concentrations in leaves [136]. Transgenic barley expressing the Arabidopsis ZIP1 iron/zinc transporter, despite having smaller seeds, accumulated twice the amount of zinc and iron as wild-type plants [137]. In contrast, constitutive overexpression of barley ZIP7 increased the zinc content of the grain by 50%, but had negligible effect on the iron content regardless of the abundance of zinc in the soil, showing that iron and zinc are not always co-absorbed [138]. Interestingly, expression of the Arabidopsis putative zinc transporter MTP1 in barley led to a dramatic short-term increase in the amount of

Biotechnology and Nutritional Improvement of Crops. Table 11 Transgenic plants with enhanced mineral levels [23]

Species	Genes (source)	Promoters	Mineral content in seeds (and increase relative to wild type)
<i>Iron</i>			
Corn (<i>Zea mays</i>)	<i>ferritin</i> (soybean; <i>Glycine max</i>) + <i>phytase</i> (<i>Aspergillus niger</i>)	Rice glutelin-1	38 µg/g DW (2-fold)
Rice (<i>Oryza sativa</i>)	<i>ferritin</i> (soybean),	Rice gluB-1	38.1 µg/g DW (3-fold)
		Corn Ubi-1	No increase in seeds
		Rice GluB-1	34.7 µg/g DW (4.4-fold)
		Rice Glb-1	27 µg/g DW (3-fold)
	<i>ferritin</i> (pea; <i>Pisum sativum</i>),	CaMV-35S	31.3 µg/g DW (4.82-fold)
	<i>ferritin</i> (common bean; <i>Phaseolus vulgaris</i>) + <i>phytase</i> (<i>Aspergillus fumigatus</i>)	Rice glutelin-1	22.07 µg/g DW (2-fold)
Tobacco (<i>Nicotiana tabacum</i>)	<i>nas1</i> (Arabidopsis; <i>Arabidopsis thaliana</i>) + <i>ferritin</i> (common bean)	CaMV35S + rice globulin	7 µg/g DW (6.3-fold) (in polished rice)
	<i>nas1</i> (barley; <i>Hordeum vulgare</i>)	CaMV35S	(2.3-fold in leaves)
	<i>nas1</i> (Arabidopsis)	CaMV35S	(1.5-fold in leaves)
<i>Calcium</i>			
Carrot (<i>Daucus carota</i>)	sCAX 1 (Arabidopsis)	CaMV35S	3.9 mg/g DW (1.6-fold) (in carrot)
Lettuce (<i>Lactuca sativa</i>)	sCAX 1 (Arabidopsis)	Cell division cycle (cdc2a)	18.9 mg/g DW
Potato (<i>Solanum tuberosum</i>)	sCAX 1 (Arabidopsis)	CaMV35S	1.7 mg/g DW (3-fold) (in tuber)
	CAX2B chimeric (Arabidopsis)	CaMV35S	2.5 mg/g DW (3-fold) (in tuber)
Rice	sCAX 1 (Arabidopsis)	CaMV35S	not determined
Tomato (<i>Solanum lycopersicum</i>)	CAX 4 (Arabidopsis)	CaMV35S	1.8 mg/g DW (in fruit)

Source: Data updated from [23]

zinc stored in the roots under high zinc loads, but no difference in the amount of zinc in the seeds over the long term [139].

Several different approaches can be envisaged to enhance the uptake and storage of selenium, based on the multiple inorganic and organic sources of selenium in the soil and the manner in which they are interconverted [140]. ATP-sulfurylase (APS) is rate limiting for selenate reduction and accumulation in most plants, so the overexpression of this enzyme can increase the uptake of selenate [141]. Selenocysteine methyltransferase (SMT) converts selenocysteine

into selenium-methylselenocysteine (MetSeCys), a nontoxic form found at high levels in the selenium-hyperaccumulator, *Astragalus bisulcatus*, so the overexpression of this enzyme would be a suitable approach for increasing the accumulation of organic selenium.

Pilon-Smits et al. [141] expressed Arabidopsis APS in Indian mustard, resulting in a threefold increase in selenium levels in leaves and greater tolerance for high selenate levels in the soil. The levels of organic selenium also increased because of the increased capacity for selenate reduction [141, 142]. Indian mustard plants

overexpressing both APS and SMT accumulated 10-fold more MetSeCys than normal, reflecting the increased uptake of selenate and its conversion to MetSeCys as well as the reduction of selenite [143]. More recently, McKenzie et al. [144] expressed *Brassica oleracea* APS and *Astragalus bisulcatus* SMT in tobacco plants supplied with selenate. The expression of SMT increased total selenium levels up to 4-fold, and whereas the expression of APS did not increased total selenium level, when combined with the SMT, a greater proportion of selenium was converted into MetSeCys.

The calcium content of crops has been enhanced by expressing specific $\text{Ca}^{2+}/\text{H}^{+}$ antiporters located in the vacuolar membrane (Table 11). For example, the Arabidopsis cation exchanger 1 antiporter (sCAX1) [145], enhances the level of bioavailable calcium when expressed in transgenic potato tubers and carrot tap-roots [33, 146–148]. The same protein has been expressed in transgenic lettuce, which accumulated higher levels of calcium than wild-type leaves without impacting on flavor or crispness [149]. Kim et al. [150] constructed a chimeric Arabidopsis gene (CAX2B) by combining a truncated N-terminal portion of CAX2 with the “B” domain from CAX1. Transgenic potatoes expressing this recombinant construct accumulated calcium without affecting the levels of related cations such as Mn^{2+} . Transgenic tomatoes expressing the Arabidopsis CAX4 gene also accumulated higher levels of calcium than wild-type fruits [150].

Mineral Storage in Sink Tissues In cereal grains, minerals are predominantly stored in the bran (embryo and aleurone layer) rather than the endosperm, which means that much of the nutritional value of cereals is lost during polishing [151]. Encouraging plants to absorb more minerals from the soil is therefore not sufficient to increase the nutritional value of food. In addition to improving mineral uptake, cereals must be engineered to accumulate minerals in the endosperm.

Minerals in plants are found both as free ions in solution and as complexes with dedicated proteins that have evolved for the specific function of mineral transport and storage (protecting the plants against both mineral deficiency and overload). Ferritin, e.g., is a 450-kDa protein consisting of 24 subunits that form a shell, enabling the storage of up to 4,500 Fe^{3+} ions as crystallites with hydroxide and phosphate.

Recombinant soybean ferritin has been expressed in the endosperm of several cereals allowing the accumulation of iron in the endosperm [152–155] and pea ferritin has also been constitutively expressed in rice [156]. In the best cases, the level of bioavailable iron exceeded 35 mg kg^{-1} .

Combined Strategies to Increase Mineral Density in Cereal Grains

Although increasing the uptake of iron and the ability of plants to accumulate iron both work as individual strategies to improve the mineral content of cereal crops, there are limitations when each strategy is applied alone. Increasing the uptake of iron without considering its distribution will result in the hyperaccumulation of iron in vegetative tissues as well as the seeds, eventually resulting in overload and toxicity. Conversely, the overexpression of ferritin without compensating for the increased iron storage capacity results in the sequestration of free iron needed by plant cells for normal physiological functions, inhibiting photosynthesis and causing chlorosis even if plenty of iron is available in the soil [154]. These issues can be overcome by combining the strategies, i.e., increasing both uptake and storage capacity in the same plant. For example, the combined expression of Arabidopsis nicotianamine synthase and soybean ferritin in rice resulted in rice grains with 6.3-fold more iron in the polished endosperm than wild-type plants (and also elevated levels of zinc), but no adverse effects [157].

Strategies to Ensure Stored Minerals Are Bioavailable

Increasing the levels of minerals in plants does not necessarily increase their bioavailability, i.e., the proportion of the mineral that can be absorbed in the human gut [23]. In some cases, bioavailability depends on the chemical form in which a mineral is presented. For example, selenomethionine is a more bioavailable form of selenium than any inorganic source [18], and heme iron is more bioavailable than nonheme iron [158]. For cereals in particular, bioavailability reflects the presence of antinutritional compounds that inhibit absorption, such as phytate and oxalic acid, which chelate divalent cations (Table 10). It has been shown that high levels of such compounds can reduce mineral bioavailability to the extent of causing marginal deficiency diseases even if absolute mineral levels are adequate [159]. This can easily be overcome with a varied

diet, but is particularly challenging in developing country settings where a monotonous diet of staple cereals is commonplace.

Strategies to tackle the presence of antinutritional compounds include conventional breeding to reduce the level of phytate in cereals, and biotechnology-based approaches to either reduce phytate levels or increase the levels of nutritional enhancers that counteract the effect of phytate. For example, natural variation in levels of the nutritional enhancer inulin has been investigated to increase the bioavailability of zinc [160]. Mutagenesis and conventional breeding have been used to generate low-phytate corn, barley, rice, and soybean [161, 162], which have 66%, 95%, 64%, and 80% less phytate, respectively, than corresponding wild-type lines, as well as beans with a 90% reduction of the normal levels of phytate but with no adverse effects on plant growth and development [163]. A *Medicago truncatula* mutant has also been bred with low levels of oxalic acid and therefore 22.87% higher calcium bioavailability [164]. Phytate levels have also been reduced in transgenic cereals by expressing a recombinant fungal enzyme (phytase) that degrades the compound. This strategy has been used to increase iron bioavailability in wheat (86% reduction in phytate [165, 166]) and corn (23% reduction in phytate [167]). The combined expression of ferritin and phytase was used in rice [168] and corn [169] (95% reduction of phytate) to increase iron levels and bioavailability in simulated digestion/absorption trials.

Stacking Nutritional Enhancement Traits The vast majority of transgenic plants engineered for nutritional enhancement have been created with the specific intention of tackling one particular nutrient (or class thereof). In many cases, this has involved the transfer of a single gene. In others, discussed above, two transgenic lines have been crossed to combine enhancements in an additive or synergistic manner, e.g., enhancing iron uptake and accumulation, or enhancing two branches of a metabolic pathway to increase the levels of folate. An alternative approach is supertransformation (the transformation of transgenic plants with additional transgenes), which has been used to produce VLC-PUFAs in *Arabidopsis* [88]. Both methods have two major drawbacks – the long

and labor-intensive development process involving several breeding generations, and the fact that the different transgenes are unlinked, leading to segregation in subsequent generations [170]. Cotransformation refers to the simultaneous introduction of two or more transgenes, and its major advantages are that plants carrying multiple transgenes are produced in one generation and all the transgenes are likely to integrate at the same locus, thus preventing segregation. Cotransformation has been used to introduce up to seven transgenes simultaneously for the purpose of nutritional enhancement, in this case, the enhancement of carotenoid synthesis in canola [99], but even in this case, the aim was to modulate the levels of a single nutrient, β -carotene.

It is clear that, regardless of the success of experiments involving individual nutrients, the deployment of a transgenic plant line enhanced for a single nutrient will only serve to shift the problem of nutrient deficiency onto a different compound. In order to address the challenge of micronutrient deficiency in a global manner, the next objective must be to enhance staple crops for all essential nutrients simultaneously. Zhu et al. [95] reported a unique and surprisingly straightforward approach to this challenge based on combinatorial nuclear transformation in corn. They chose the carotenoid biosynthetic pathway and transformed corn with a collection of five transgenes encoding the enzymes phytoene synthase, phytoene desaturase, lycopene β -cyclase, β -carotene hydroxylase, and β -carotene ketolase. Unlike other transformation experiments where the aim is to achieve a defined outcome, here the aim was to generate maximum diversity, i.e., a library of transformants expressing different combinations of transgenes. Transgenic plants expressing different enzyme combinations and showing distinct metabolic phenotypes were generated, allowing the identification and complementation of rate-limiting steps in the pathway. Individual transgenic lines were identified with extraordinarily high levels of β -carotene (as discussed earlier) and other carotenoids, providing the mechanism to generate plants with high levels of different nutrients in the same experiment. The same group expanded this principle by breeding selected transgenic lines with selected non-transgenic cultivars to generate lines with unprecedented levels of zeaxanthin [34] and by repeating the process with additional

transgenes to identify plants simultaneously enhanced for multiple vitamins. Using four transgenes encoding enzymes from three metabolic pathways (corn PSY and bacterial CrtI for carotenoid synthesis, rice DHAR for ascorbate synthesis, and *E. coli* GCH1 for folate synthesis), Naqvi et al. [96] generated transgenic corn lines with a 407-fold increase in β -carotene (57 $\mu\text{g/g DW}$), a 6.1-fold increase in ascorbate (106.94 $\mu\text{g/g DW}$), and a 2-fold increase in folate (200 $\mu\text{g/g DW}$) compared to the non-transformed control plants.

Future Directions

Biotechnology has the potential to address some of the major elements of food insecurity both by increasing the availability of food and making that food more nutritious. The nutritional properties of plants can be improved by increasing the levels of essential amino acids, PUFAs, and vitamins, and by favoring the accumulation of minerals in a bioavailable form. Golden Rice and Multivitamin Corn are key developments in the history of nutritional enhancement, providing models for the development of crops that will particularly benefit subsistence farmers in developing countries. It is imperative that the focus shifts away from single gene strategies and single nutrients and toward the introduction of multiple genes that simultaneously enhance multiple pathways, leading ultimately toward the creation of transgenic crops that are in every sense of the word nutritionally complete.

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Breeding in Beef Cattle

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Glossary

Beef Improvement Federation (BIF) accuracy A metric of accuracy that is more conservative than true accuracy. It is linearly related to prediction error variance.

Bio-economic index A collection of EPD that are relevant to a breeding objective whereby each EPD is multiplied by an economic weight.

Composite A crossbred animal. Generally thought of in terms of a pedigreed seedstock animal that is a cross of two or more breeds.

Expected progeny difference Equivalent to half of a breeding value.

Molecular breeding value The sum of marker effects multiplied by the number of copies of a given marker.

Definition of the Subject

The beef cattle industry represents a diverse and unique sector of animal agriculture with varying breeds, production climates, and marketing objectives. The industry is not vertically integrated and thus breeding and selection decisions are controlled by individual farmers and ranchers. In the United States, the average herd size is less than 30 cows. However, there exists sound tools from which to make genetic selection decisions to ultimately make genetic change and improve profitability. These tools, some of which have been utilized for decades, are available to all beef cattle producers. The utilization of current genetic selection tools can aid in the profitability and ultimately the sustainability of beef enterprises.

Introduction

The beef cattle industry is comprised of seedstock and commercial producers. In general, genetic improvement, or accumulation of breeding value, occurs in the seedstock sector and flows to the commercial

industry via the purchase of bulls and/or semen. Less than 10% of producers in the United States utilize artificial insemination (AI). Selection decisions can be made based on a plethora of information, but the most informative are breeding values or expected progeny differences (EPDs) in the US and economic index values. There are several EPD and index values across multiple breeds.

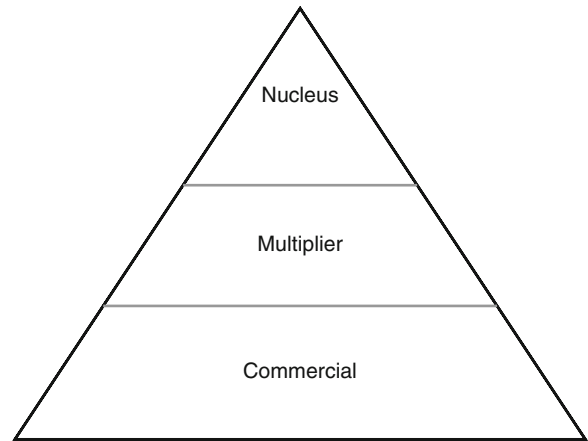
There have also been an increasing number of commercially available genomic tests made available for multiple traits. Some of these have undergone independent validation, while others have not. This technology holds the promise to increase the rate of genetic progress and to allow for selection on those traits that are expensive or challenging to measure routinely. However, there still exist several caveats to solve before this is completely brought to fruition.

Sustainability from a beef perspective will depend on economics and consumer perception. Genetic selection will need to focus on tools that aim solely at the genetic component of phenotypes and tools that apply economic parameters need to be quantified such that a return on investment can be determined. Consumer demand will ultimately be dictated by price and product quality suggesting that efficient genetic selection is needed and that selection tools need to evolve to improve end-product quality.

Structure of the Beef Industry

In other species, such as swine and poultry, the breeding pyramid is much more clearly defined than in beef cattle given formalized breeding companies. However, it still exists in beef cattle (Fig. 1) as some purebred producers have a much larger influence over the gene pool of a breed compared to others. At the nucleus level, animals (particularly sires) are produced for use at the multiplier level although some nucleus animals are sold directly to commercial herds. The nucleus herds are the drivers of genetic change. The multiplier herds, as the name implies, multiply genes from the nucleus populations to produce animals for use in the commercial sector. It is possible, and does occur, for animals from multipliers to enter into nucleus herds.

There are four main pathways from which herds can influence the rate and direction of genetic change: producing sires of sires, sires of dams, dams of sires,



Breeding in Beef Cattle. Figure 1

The breeding pyramid representing the three broad segments of the beef industry

and dams of dams. The most influential is sires of sires. As an example, Marquez et al. [1] characterized the population structure of the Red Angus breed and found that indeed it could be divided into nucleus and multiplier herds and that only 30% of the total herds produced sires of sires.

Basic Principles of Genetic Improvement

In order to make genetic improvement the target trait (s), observable or measureable characteristics of an animal, must display variation. The goal of genetic improvement is to improve the phenotype, observed category or measured level of performance for a trait, by improving the genotype or genetic makeup of an animal to best fit the system and to make the best product for consumers. The phenotype (P) of an animal is comprised of both genetic (G) and nongenetic factors such as the environment (E) such that

$$P = G + E$$

These two primary factors, G and E, can be further divided into additive (A), dominance (D), and epistatic (I) genetic effects and both permanent (E_p) and temporary (E_T) environmental effects such that

$$P = G_A + G_D + G_I + E_p + E_T$$

Temporary genetic effects can be thought of as differences in feeding regime or climate and are generally accounted for by contemporary groups whereas PE

are long lasting changes that influence future performance (i.e., the loss of one-quarter of the udder). Contemporary groups are considered to be a group of animals that have been subjected to the same environmental effects or managed alike such as being born in the same year, season, and herd, being of the same sex, and fed the same diet.

Trait Types

There are two broad categories of traits, simply inherited and polygenic traits. Simple traits are expressed qualitatively, controlled by only one or two genes, and are typically influenced little by environment. In contrast, polygenic traits are controlled by many genes, are greatly influenced by the environment, and are quantitative in nature (i.e., they are expressed numerically or on a continuous scale).

Simple Traits

In beef cattle, the phenotype of horns is controlled by dominance wherein the horned allele is recessive. If a heterozygous male is mated to a heterozygous female the resulting calf has a 25% chance of being horned and a 75% chance of being polled (absence of horns). This is illustrated in the Punnett Square below where

P denotes the polled allele, and p represents the horned allele.

	P	p
P	PP	Pp
p	pP	pp

Black and red coat color is controlled in the same manner where black is dominant to red such that homozygous (BB) and heterozygous (Bb) animals are black and only homozygous animals for the recessive allele (bb) are red.

Similarly, many genetic defects in cattle are also recessive in nature. A list of known genetic defects in beef cattle can be found in Table 1. Use the example of Neuropathic Hydrocephalus (NH), a recessive lethal mutation found in Angus cattle. If a heterozygous bull (Nn) is mated to a homozygous normal female (NN) then the resulting offspring would be 100% normal (i.e., not afflicted) with 50% of them being homozygous and the other 50% heterozygous.

	N	n
N	NN	Nn
n	nN	nn

Breeding in Beef Cattle. Table 1 Genetic defects currently monitored by US breed associations

Genetic abnormality	Primary breed(s) of incidence	Lethal or nonlethal	Mode of inheritance	DNA test available
Alpha (α)-mannosidosis	Red Angus	Lethal	Simple recessive	Yes
Arthrogryposis multiplex (AM)	Angus and derivatives	Lethal	Simple recessive	Yes
Beta (β)-mannosidosis	Salers	Lethal	Simple recessive	Yes
Fawn calf syndrome (FCS)	Angus	Nonlethal	Simple recessive	Yes
Neuropathic hydrocephalus (NH)	Angus	Lethal	Simple recessive	Yes
Hypotrichosis (hairless calf)	Hereford	Nonlethal	Simple recessive	No
Idiopathic epilepsy	Hereford	Nonlethal	Simple recessive	Yes
Osteopetrosis	Angus and Red Angus	Lethal	Simple recessive	Yes
Protoporphyria	Limousin	Nonlethal	Simple recessive	Yes
Pulmonary hypoplasia and anasarca (PHA)	Maine-Anjou and Shorthorn	Lethal	Simple recessive	Yes
Tibial hemimelia (TH)	Shorthorn and Maine-Anjou	Lethal	Simple recessive	Yes

Coat color in shorthorn cattle is controlled by co-dominance. There are three possible phenotypes that can result from the pairing of two alleles, red (R) and white (W). When two R or two W alleles pair together the resulting animals is either red (RR) or white (WW), respectively. However, the heterozygous animals (RW or WR) or an intermediate color, a mixture of both red and white called “roan.” The example below illustrates the genotypes and phenotypes that would be expected from the mating of a roan bull to a roan cow. In this example there is a 25% chance the calves will be red, 50% chance they will be roan, and 25% chance the will be white.

	R	W
R	RR	RW
W	WR	WW

Sex-influenced traits have different expressions in different sexes given the same genotype. A classic example of a sex-influenced trait in beef cattle is the presence or absence of scurs. Here the scured allele (Sc) would appear to be dominant in males but recessive in females.

Males	Females
SS = no scurs	SS = no scurs
SSc = scurs	SSc = no scurs
ScSc = scurs	ScSc = scurs

Polygenic Traits

The number of gametes that an individual can produce is equal to 2^n where n is the number of heterozygous loci. The number of possible genotypes that can be produced from any one mating is equal to $3^n \times 2^m$ where n is the number of loci where both parents are heterozygous and m is the number of loci where only one parent is heterozygous. From this, it is obvious that from a single mating there can arise numerous possible genotypes.

Number of genes	Individual heterozygous at every loci	Both individual heterozygous
	Number of gametes	Number of genotypes

1	2 (2^1)	3 (3^1)
2	4 (2^2)	9 (3^2)
10	1,024 (2^{10})	54,049 (3^{10})

Basics of an EPD

A breeding value (BV) is cumulative additive value of an animal. A transmitting ability (TA) is the average of gametes an individual passes to offspring.

$TA = 1/2BV$

In beef cattle, a TA is referred to as an expected progeny difference (EPD).

EPDs allow for the comparison of animals within a breed for their genetic potential as parents for a given trait. EPDs have existed in the beef industry for decades and their use has produced intended genetic change in many traits.

Many traits (e.g., weaning weight, yearling weight (YW), ultrasound measurements, etc.) must be recorded within certain age windows (ranges when it is acceptable to measure animals). Animals measured outside of defined age windows will not have their own record incorporated into an EPD calculation. This allows for a fair comparison of animals. Specific age windows can be found on the corresponding breed association Web site. Records are then adjusted to a constant endpoint, most generally age (Table 2).

Too often, seedstock producers and bull buyers focus on actual weights and ultrasound data when selecting sires. Expected progeny differences provide a measure by which animals within a breed can be compared to one another for their genetic potential as parents for specific traits. EPDs incorporate multiple

Breeding in Beef Cattle. Table 2 Beef Improvement Federation (BIF) standard adjustment factors for birth and weaning weight

AOD	Birth weight	Male	Female
2	+8	+60	+54
3	+5	+40	+36
4	+2	+20	+18
5–10	0	0	0
11 and older	+3	+20	+18

sources of information, including full pedigree, an animal's own record, and progeny information. As additional sources of information become available, the accuracy of the EPD value increases. Prior to a National Cattle Evaluation (NCE), animals are given interim EPDs. During a genetic evaluation, all pedigree information would be included.

Pedigree estimate:

$$\begin{array}{ccc} \text{Sire EPD} = 0.20 & \text{Dam EPD} = 0.10 & \\ \swarrow & & \searrow \\ \text{Progeny EPD} = \left(\frac{0.20 + 0.10}{2} \right) = 0.15 \end{array}$$

Pedigree estimate + animal record:

$$EPD_I = (0.5 * EPD_S) + (0.5 * EPD_D) + (0.5 * \phi)$$

Where EPD_I is the EPD for some individual I, EPD_S is the EPD for the sire of animal I, EPD_D is the EPD for the dam of animal I, and ϕ is the Mendelian Sampling effect. The phenomena of Mendelian sampling arises due to the fact that each parent passes a sample half of its alleles to its offspring and every allele has an equal likelihood of being passed on. This effect can be quantified using contemporary group deviations and is a measure of how much better or worse an animal is compared to the average of his parents. One could envision a scenario where an animal could receive only the most desirable alleles from both parents resulting in a favorably large Mendelian sampling effect or the exact opposite which could result in an unfavorably large sampling effect. Perhaps the best example is a set of flush mates. Although all of them have the same pedigree estimate, they differ considerably in terms of performance and consequently their EPD, once they have a record, differ due to Mendelian sampling.

When using EPD it is important to understand that the role of EPD is to provide a measure of comparison within a breed. To compare animals across breeds, estimates from the US Meat Animal Research Center (MARC) can aid in determining differences between EPD of different breeds (Table 3). These across breed adjustment factors, adjusted to an Angus basis, are updated annually and can be found at <http://www.beefimprovement.org/proceedings.html>.

Example:

If a Hereford bull has a birth weight EPD of 1.5 and a Simmental bull has a birth weight EPD of 1.0 these

Breeding in Beef Cattle. Table 3 2008 Adjustment factors for comparison of expected progeny difference (EPD) across various breeds

Breed	Birth weight	Weaning weight	Yearling weight	Milk
Angus	0.0	0.0	0.0	0.0
Charolais	9.6	39.0	47.3	2.9
Gelbvieh	4.4	5.0	-22.4	7.0
Hereford	2.7	-2.9	-12.8	-15.3
Limousin	4.0	-3.8	-27.8	-11.9
Red Angus	2.8	-5.2	0.9	-3.9
Simmental	5.4	23.3	16.9	13.9

Source: Adapted from Kuehn et al. [2]. More breeds and more traits are available in the full results from the US Meat Animal Research Center

adjustment factors can be used to approximate what these two bulls birth weight EPD would be on an Angus basis so that they can be compared. On an Angus basis, the Hereford bull would have a birth weight EPD of 4.2 ($1.5 + 2.7$) and the Simmental bull would have a birth weight EPD of 6.4 ($1.0 + 5.4$). Therefore, it can be expected in this scenario that the Hereford bull would sire calves that are 2.2 lbs. lighter at birth. This table can be an effective tool to determine differences in weight and milk potential between major US breeds. This information can be used to help determine which breed(s) are better suited to different environments. For instance, in a low input environment, breeds with a negative adjustment factor for milk might be more desirable.

Breed Average and Percentile Ranks

Table 4 illustrates a percentile rank table. These will be different for every breed and will change yearly with the addition of new animals with performance information recorded. The 50th percentile represents breed average. If an animal is in the top 1% for a given trait then it can be said that 99 animals in a hundred are "worse" for that trait. Conversely, if an animal is in the 95th percentile then it can be said that 94 in 100 animals will be better than him/her for that trait. Knowledge of percentile table gives you an idea of how an individual ranks within a breed for a specific trait or index. However, it may

Breeding in Beef Cattle. Table 4 Percentile rank

Top %	CED	BW	WW	YW	Milk
1	14	−2.5	67	117	34
5	11	−.9	59	105	30
10	10	−.1	55	99	28
20	9	.7	50	92	25
50	6	2.2	42	79	20
75	3	3.4	36	69	16
95	−2	5.2	26	50	10

CED calving ease direct, *BW* birth weight, *WW* weaning weight, *YW* yearling weight, *Milk* maternal milk (maternal component of weaning weight)

not be beneficial to choose extreme animals. For instance, even though a sire might be in the top 1% of the breed for Milk, his Milk value may be too extreme for your production environment.

EPD Definitions

	BULL A	BULL B
Calving ease direct	10	6
Birth weight	+2.0	+3.5
Weaning weight direct	20	+22
Yearling weight	+40	+52
Yearling height	.3	.6
Milk	+3	−2
Maternal weaning weight	+13	+9
Gestation length	−.1	+1.1
Calving ease maternal	4	6
Mature daughter height	+.5	+1.0
Mature daughter weight	0	+30
Scrotal circumference	+.1	−.45
Heifer pregnancy	6	9
Carcass weight	+2.0	+20
Percent retail cuts	0	+.2
Marbling	0	−.3
Ribeye area	+.06	+1.6

Fat thickness	−.01	−.09
Tenderness	−.1	.1
Days to finish	15	10
Stayability	10	6
Maintenance energy	0	10
Docity	6	2

Calving ease direct – Bull A should have 4% more unassisted births from first-calf heifers than Bull B. While birth weight is an indicator of calving ease, it does not tell the whole story. Calving ease is an economically relevant trait. Producers should not use both birth weight and calving ease EPD together since the birth weight EPD is already used in the calculation of calving ease.

Birth weight – Bull B's calves would be on the average 1.5 lb heavier at birth. Normally, producers should select bulls for use on heifers that are at or less than the breed average for birth weight. Keep in mind that when crossing breeds, heterosis or hybrid vigor can increase birth weights 10–15% over a straight-bred average.

Weaning weight direct – Calves from Bull B should average 2 lb more on adjusted weaning weights because of additional growth. Because of the low accuracy associated with yearling bulls, the amount of emphasis placed on such a small difference should be limited. These EPDs are virtually the same even if the accuracies were high.

Yearling weight – Bull B's calves should average 12 lb heavier at 1 year of age.

Yearling height – Bull B's calves should be 0.3 in. taller on average at a year of age compared to the offspring of Bull A. Height measurements are taken at the hip. Height (the actual measurement and not the EPD), along with age, is used to calculate frame score.

Milk – Daughters from Bull A should produce calves that are 5 lb (the difference between +3 and −2) heavier at weaning. This is not a measure of pounds of milk but rather weaning weight due to milk production. This 5 lb, unlike the weaning weight figure attributed to growth from the bull, is the result of differences in the daughters' milk production and mothering ability. Excessively high milk levels in low input environments should be discriminated against due to increased nutrient requirements of cows.

Total maternal (maternal weaning weight) – Daughters from Bull A will produce calves that are 4 lb heavier at weaning because of their combined genetics for growth and milk. This is a calculated figure of one-half the bull's weaning weight direct EPD plus his milk EPD. For example, Bull A has a maternal weaning weight value of 13 which is equal to half of his weaning weight direct EPD ($20/2 = 10$) plus his milk EPD [3].

Gestation length – Calves from Bull A should have a 1-day shorter gestation.

Calving ease maternal – Bull B's daughters should calve as first-calf heifers with 2% more unassisted births (6–4) than the daughters of Bull A.

Mature height – Bull B's daughters should be .5 in. taller at maturity.

Mature weight – Bull B's daughters should be 30 lb heavier when mature.

Scrotal circumference – Bull calves from Bull A should have .55 cm larger adjusted scrotal circumferences. Scrotal circumference is an indicator of the age of maturity of a bull's daughters. Bulls with larger scrotal circumference should have daughters that reach puberty earlier.

Heifer pregnancy – Daughters of Bull B are 3% more likely to become pregnant as heifers.

Carcass weight – Bull B should produce calves that have 18 lb more adjusted carcass weight.

Percent retail product – The calves from Bull B should yield 0.2% more closely trimmed, boneless retail cuts from the round, loin, rib, and chuck. Some breeds may report a Yield Grade (YG) EPD. The same factors (back fat, ribeye area, and carcass weight) would be included but a lower YG is more desirable as opposed to percent retail product where a higher value is more desirable. In either percent, retail product or YG fat thickness contributes the most to these two calculations. Consequently, selecting for decreased YG or increased percent retail product will lead to leaner animals so caution should be used to avoid extremely lean replacement females.

Marbling – Calves from Bull A should have a marbling (MARB) score of >0.3 . Marbling scores range from 1.0 which is devoid of marbling and a utility quality grade to 10.9 which is abundant marbling and a prime + quality grade. For example, if calves sired by Bull B had a marbling score of 5.0 then

calves sired by Bull A are expected to have a marbling score of 5.3. Ultrasound EPDs were calculated for a number of breeds for traits of ribeye area (REA), fat, and intramuscular fat (IMF), which is correlated to marbling, but now the majority of breeds use these ultrasound measurements in the calculation of carcass EPDs. Therefore, instead of seeing both an IMF EPD and a marbling EPD you just see the marbling EPD but it has ultrasound measurements included in the calculation.

Ribeye area – At a given end point, calves from Bull B should have ribeye areas that are 1.54 square inches larger than Bull A's calves.

Fat Thickness – At a given end point, calves from Bull A should be .08 in. fatter when measured at the 12th rib. This would be less desirable on a carcass animal, but extremely lean females going back into a cowherd may also be undesirable.

Tenderness – Calves sired by Bull A should produce meat that is more tender than that of calves sired by Bull B by 0.2 lbs. of shear force. Tenderness is measured by Warner Bratzler Shear Force (WBSF) that is reported in the pounds of force required to cut through a one inch thick piece of meat. A lower value is more desirable.

Days to finish – Calves sired by Bull B should spend 5 fewer days on feed to reach a constant fat endpoint.

Stayability – A measure of reproductive longevity. Daughters of Bull A are 4% more likely to stay productive in the herd to age 6.

Maintenance energy – The Red Angus Association of America calculates a Maintenance Energy (ME) Expected Progeny Difference (EPD) that indicates differences in the Mcal/month needed for maintenance due to mature size (corrected for body condition score) and milking ability (The Rancher's Guide to EPD available at www.redangus.org). A much simpler way to think of it is that a bull with a ME EPD of +10 compared to one that is +0 will produce daughters that will require approximately 11 more pounds of average quality forage per month (assuming average quality forage = .86 Mcal/lb.).

Docility – Bull A should sire 4% more calves that have a temperament in the most docile score than Bull B. The actual measurement of docility is recorded either at weaning or at yearling (depending on the breed association) and is categorized as the

animals’ behavior as they enter, are restrained in, and exit the chute.

Beef Improvement Federation (BIF) temperament scoring system.

1. Docile – Mild disposition – gentle and easily handled. Stands and moves slowly during processing, undisturbed, settled, and somewhat dull and does not pull on the headgate when in the chute – exits the chute calmly.
2. Restless – Quieter than average but slightly restless, might be stubborn during processing, might try to back from the chute, pulls back on the headgate, some tail flicking, exits the chute promptly.
3. Nervous – Typical temperament – manageable but nervous and impatient with a moderate amount of struggling, movement, and tail flicking as well as repeated pushing and pulling on the headgate – exits the chute briskly.
4. Flighty – Wild, jumpy and out-of-control, quivers and struggles violently, might bellow and froth at the mouth, continuous tail flicking, defecates and urinates during processing, frantically runs the fence line and might jump when penned individually, exhibits long flight distance, and exits the chute nervously.
5. Aggressive – Similar to Score 4 but with added aggressive behavior, fearful, extreme agitation, continuous movement that might include jumping and bellowing while in the chute, exits the chute frantically, and might exhibit attack behavior when handled alone.
6. Very Aggressive – Extremely aggressive temperament. Thrashes about or attacks wildly when confined in small, tight places. Pronounced attack behavior.

Accuracy

The uncertainty surrounding early predictions of genetic merit are a result of Mendelian sampling. Every animal is passed a random sample of alleles from each parent, half coming from the dam and half from the sire. An estimate of the average effect of what was passed from parent(s) to offspring in the form of pedigree estimates can be calculated, but the certainty of how correct this estimate is (i.e., the accuracy) is low. As more information is collected, such as an

individual’s own record and data from progeny, accuracy increases. For lowly heritable traits, like measures of reproduction, it can take a considerable number of offspring to reach high BIF accuracy levels, given that the BIF scale is more conservative than true accuracy (*r*) as illustrated in Table 5. To calculate *r* in the context of progeny test sires the following equation can be used where *n* is the number of progeny:

$$r = \sqrt{\frac{nh^2}{4 + (n - 1)h^2}}$$

To convert BIF accuracy to true accuracy (*r*) the following equation can be used:

$$r = \sqrt{1 - (1 - \text{BIF})^2}$$

Theoretically, accuracy is the correlation between an animal’s predicted EPD and its true EPD. However, it is much simpler to think of it as a measure of risk indicating how much an animal’s EPD may change with the inclusion of additional information. Accuracy is not an indication of how variable a particular sire’s calves will be but rather how the estimate of an animal’s EPD is likely to change. As the accuracy value increases, the amount by which an EPD is likely to change

Breeding in Beef Cattle. Table 5 Approximate number of progeny needed to reach accuracy levels (true (*r*) and the Beef Improvement Federation standard) for three heritabilities (*h*²)

Accuracy		Heritability levels		
R	BIF	h ² (0.1)	H ² (0.3)	h ² (0.5)
0.1	0.01	1	1	1
0.2	0.02	2	1	1
0.3	0.05	4	2	1
0.4	0.08	8	3	2
0.5	0.13	13	5	3
0.6	0.2	22	7	4
0.7	0.29	38	12	7
0.8	0.4	70	22	13
0.9	0.56	167	53	30
0.999	0.99	3,800	1,225	700

decreases. Possible change values differ for every trait and for every breed (e.g., an Angus bull with an accuracy of 0.30 may have a different possible change value than a Limousin bull with the same accuracy value for the same trait). Possible change tables are available on breed association Web sites.

Example: Possible Change in the Marbling EPD of a Limousin Sire

Assume that a young Limousin sire has a marbling EPD of 0.10 with an accuracy of 0.20. Using the values in Table 6, it is expected that 2/3 of the time his true EPD would fall within ± 0.20 (one standard deviation) of his printed EPD or between -0.10 and 0.30 . If there is 2 in 3 chance that the true EPD is between -0.10 and 0.30 then there must be 1 in 6 chance that his true EPD is below -0.10 and a 1 in 6 chance that his true EPD is above 0.30 .

Multiple-Trait Selection

Through genetic correlations, selection for one trait can influence other traits. This knowledge is useful when practicing multiple-trait selection. There are three primary methods of multiple-trait selection: tandem selection, independent culling levels (ICLs), and selection indexes.

Breeding in Beef Cattle. Table 6 Accuracy related to possible change in Limousin cattle

BIF accuracy	Ribeye area EPD possible change	Marbling score EPD possible change
0.0	0.46	0.24
0.1	0.41	0.22
0.2	0.37	0.20
0.3	0.32	0.17
0.4	0.28	0.14
0.5	0.23	0.12
0.6	0.18	0.10
0.7	0.14	0.07
0.8	0.09	0.05
0.9	0.05	0.02

Source: www.nalf.org

Tandem selection. Tandem selection is the process of placing selection pressure on one trait and once the desired level of the trait under selection has been reached. Then selection for a new trait would begin. This is the simplest form of multiple-trait selection and the most inefficient. The two (or more) traits involved are selected for independently such that progress made in one trait could be eroded once selection for another trait becomes the focus of the breeding scheme. This is the poorest way to select for multiple traits.

Independent culling levels. Independent culling levels (ICLs) describe the process where threshold criteria for multiple traits are set and any animal not meeting all criteria (threshold levels for all traits) are excluded as candidates for selection. Although this ensures a certain level of superiority across multiple traits it may cull a particular animal that is just below the threshold level for one trait.

Economic Index

An economic index is a collection of EPDs that are weighted by their economic value such that traits with a greater impact on a production goal have a larger economic weight associated with them. Assume that there is an index centered on improving profit potential of terminal animals sold on a grid. In this particular index, the traits of economic importance might be yearling weight (YW), ribeye area (REA), marbling (MARB), and external fat (BF). Below is an example of how this index might look.

$$I = \text{EPD}_{\text{YW}} \times a_{\text{YW}} + \text{EPD}_{\text{REA}} \times a_{\text{REA}} + \text{EPD}_{\text{MARB}} \times a_{\text{MARB}} + \text{EPD}_{\text{BF}} \times a_{\text{BF}}$$

Where I is the index value, EPD_{YW} is the animal's EPD for yearling weight, and a_{YW} is the economic weight associated with trait yearling weight. The same approach is used for the other traits in this index, MARB and BF, where the animal's EPDs for these traits are multiplied by an economic weight. The economic weights are derived by computer simulation work to determine the economic value of changing particular traits.

Several breeds publish economic indexes including Angus, Hereford, Gelbvieh, Charolais, Simmental, and

Limousin. Each index has an intended purpose and is catered toward particular breeding objectives.

An addition the breeding objective of beef cattle in the future will likely be some measure of environmental impact, such as green house gas (GHG) emissions. There are conflicting estimates of how much beef cattle production contributes to worldwide GHG production, but there are convincing estimates that suggest that per unit of product, beef cattle production is more environmentally friendly now than at any time point in the past despite decades of artificial selection to increase output. Figure 2 illustrates that in 30 years, from 1977 to 2007, beef production has increased while the number of cows has decreased. During the same three decades, the resources needed for beef production (land, water, feed) decreased along with gas emissions and the carbon footprint [3].

Breed Selection

Correct breed selection is the critical first step to initializing a crossbreeding system. Choosing a breed(s) is dependent upon:

- 1. Production and marketing goals
- 2. Production environment
- 3. Available feed and labor resource

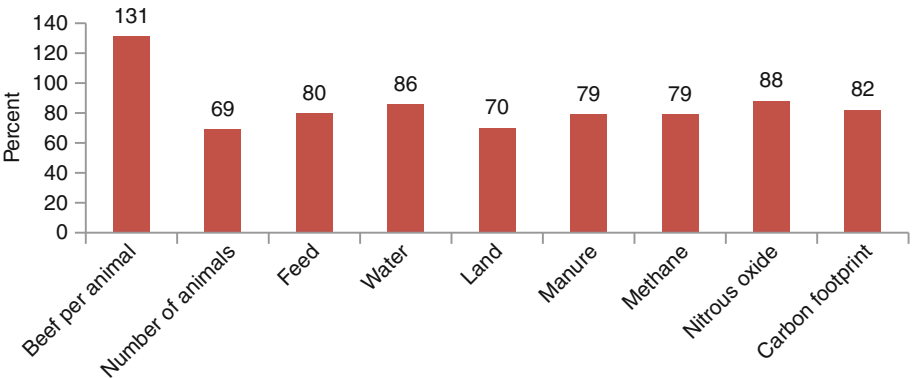
Choosing a breed that is best suited to your production environment is dependent on several factors including the availability of feed, and level of stress (temperature, amount of moisture, etc.). Table 7

outlines the biological type of cattle that are best suited for particular levels of feed resources and stress.

The decision of whether or not to utilize a particular strategic system of crossbreeding depends upon individual production goals. In order to take advantage of breed complementarity, breeds must be paired such that they excel in different areas that are critical to the overall production goal(s). For instance, if the goal were to sell calves at weaning then it would make sense to use a breed, most likely Continental, which will maximize direct weaning weights. However, this purebred system will maximize outputs, but may require large inputs as well. With that in mind, perhaps it would make more sense from an economic perspective to use a British breed as the genetic base for all dams and use a continental breed for sires thus minimizing the input costs from the female side yet still capturing added growth in the calves due to the direct growth provided by the sire breed. This would be a very simple example of a crossbreeding system.

Matching Biological Type to Environment

Benefits of heterosis make it important for producers to have a crossbreeding program. It is just as important that the producer match the type of crossbred cow to the environment and management system. This can be viewed as the foundation of a crossbreeding program. If the biological type does not match the resources, the system will fail, regardless how perfect the end product may be.



Breeding in Beef Cattle. Figure 2
Changes in metrics of beef production from 1977 to 2007 in the United States

Breeding in Beef Cattle. Table 7 Matching genetic potential for different traits to production environments

Production environment			Traits				
Feed availability	Stress ^a	Milk	Mature size	Ability to store energy ^b	Resistance to stress ^c	Calving ease	Lean yield
High	Low	M to H ^d	M to H	L to M	M	M to H	H
	High	M	L to H	L to H	H	H	M to H
Medium	Low	M to H	M	M to H	M	M to H	M to H
	High	L to M	M	M to H	H	H	H
Low	Low	L to M	L to M	H	M	M to H	M
	High	L to M	L to M	H	H	H	L to M

Source: Adapted from Gosey [4]

^aHeat, cold, parasites, disease, mud, altitude, etc.

^bAbility to store fat and regulate energy requirements with changing (seasonal) availability of feed

^cPhysiological tolerance to heat, cold, internal and external parasites, disease, mud, and other factors

^dL low, M medium, H High

Cow weight is probably easier to understand than milk production, but research has shown that cows with the genetic propensity to milk heavily require more nutrients year round, not just when they are milking. The National Research Council (NRC) data shows that a cow producing 25 lbs. of milk at peak lactation requires 10% more feed energy than a cow producing 15 lbs. of milk at peak lactation. To see a 10% difference in feed energy with regards to mature weight it would require moving from a 1,000 lb. cow to a 1,200 lb. cow, or a change of 200 lbs. of body weight. There are breed differences in lactation yields so breed selection is critical when matching genetics to your environment. These breed differences can be found in literature from research at the Meat Animal Research Center (MARC). Moderating mature cow size and selecting for an optimal window of milk production is beneficial when it comes to cutting costs regardless of your production environment. However, in limited feed environments females with high maintenance energy requirements may also have difficulty maintaining an acceptable body condition score and rebreeding. Nugent et al. [5] determined that with limited nutrient availability, breeds with a high genetic potential for milk production had longer anestrus periods which lead to lower conception rates during a fixed breeding season. Other researchers have concluded that selection for increased milk production

past an adequate threshold is not economically or biologically efficient [6]. It can be challenging to determine if cows within a herd have too much milking potential. Other than knowledge of the genetics of sires used in the past, it is important to note the body condition score of females. Extremely thin females fed the same as those with an acceptable body condition score may produce too much milk for their environment. If a producer is constantly supplementing females to maintain body condition to ensure they will successfully breed back, this might be an indication that bulls you buy in the future should have a more moderate value of milk genetics.

Another critical aspect of fitting genetics to the production environment is regional adaptation. If natural selection is allowed to play a large role in selecting the parents for the next generation, indigenous breeds should be well suited to their production environment. An example of an indigenous breed that has thrived in number is the Nelore breed in Brazil. The Nelore breed makes up roughly 65% of the world's bovine population and is well suited to tropical conditions. With adaptation in mind, indigenous breeds can be used as the base and exotic (foreign) breeds used in strategic crossbreeding systems to change target traits such as growth or carcass attributes. A case study [7] in Zimbabwe compared indigenous breeds of Afrikaner (a breed developed in South Africa), Tuli, Nkone, and

Mashona, to breeds developed outside of the African Continent such as Brahman, Charolais, Hereford, Simmental, Aberdeen Angus, and Sussex. The results showed that indigenous breeds excelled in fitness traits (fertility and survivability) while the foreign breeds excelled in growth, feed conversion, and carcass attributes.

Crossbreeding

Heterosis

Too often heterosis (hybrid vigor) is thought to be the exclusive goal of crossbreeding. Heterosis is nothing more than an unexpected and often beneficial deviation from the average of the two parental lines. Hybrid vigor can also be thought of as the “anti-inbreeding.” Inbreeding increases uniformity by increasing homozygosity but also creates “inbreeding depression” or a general decrease in survival and reproductive traits that can be caused by a decrease in heterozygosity. Percent heterosis can be calculated as:

% Heterosis =
$$\left[\frac{(\text{crossbred average} - \text{straightbred average})}{\text{straight bred average}} \right] \times 100$$

A simple example would be the percent heterosis realized in the average weaning weight from breeding a herd of Breed A cows to a group of Breed B bulls. Let 525 lb be the average weaning weight of the F1 calves, 450 lb be the average weaning weight of the Breed A population, and 550 lb be the average weaning weight of the sire’s population.

The pounds of heterosis would be:

Pounds of heterosis =
$$525 - \left[\frac{(450 + 550)}{2} \right]$$

= 25 pounds

and the percent of heterosis would be:

% heterosis =
$$\frac{25}{[(450 + 550)/2]} = .05 \text{ or } 5\%$$

The amount of heterosis that is realized for a particular trait is inversely related to the heritability of the trait. This is logical since traits that are lowly heritable have a small additive component

Breeding in Beef Cattle. Table 8 Individual heterosis: advantage of the crossbred calf

Trait	Observed improvement	% Heterosis
Calving rate	3.2	4.4
Survival to weaning	1.4	1.9
Birth weight	1.7	2.4
Weaning weight	16.3	3.9
ADG	0.08	2.6
Yearling weight	29.1	3.8

Source: Adapted from Cundiff and Gregory [9]

(proportionally speaking) and crossbreeding takes advantage of dominance and epistatic effects. With that in mind, traits of low heritability (e.g., reproductive traits) generally benefit from heterosis the most (Table 8). They generally have a heritability of less than 10% and can be improved through the adequate use of crossbreeding systems. End-product traits on the other hand that benefit from heritability in the moderate to high range benefit less from heterosis. Another benefit of crossbreeding may be a decrease in methane production per unit of beef produced. In a comparison of the methane production per ton of live weight weaned from a 16,000 ha farm in Australia, changing from Shorthorns (mean cow weight 422 kg) to composite breed cattle in (mean cow weight 507 kg), reduced methane production per ton of weight weaned by 31%. This was largely due to higher weaning rates of composite breed females (80 vs 55%) [8].

There are three main types of heterosis:

- 1. Individual
- 2. Maternal
- 3. Paternal

Retained Heterosis Unfortunately there exists a popular misconception that heterosis exists only in the first generation of crossbreds (F1). Heterosis is *retained* in the breeding of crossbred animals and is related to the probability of alleles from different parental lines joining together. For instance, if two F1 animals are mated, heterosis in the corresponding

offspring is called *retained heterosis* and is equal to the following:

$$\text{Heterosis retained} = 1 - [(P_{S1}P_{D1}) + \dots + (P_{Sn}P_{Dn})]$$

Where P_{S1} is the proportion of the sire from breed 1 and P_{D1} is the proportion of the time from breed 1 and n is equal to the total number of breed involved.

Maternal Heterosis The offspring of an F1 female will benefit from maternal heterosis (Table 9), thought of as realized heterosis of milk production.

Paternal Heterosis Fewer examples of paternal heterosis exist and consequently crossbred sires have often been ignored. The benefit of crossbred or composite sires lies in their ability to inject heterosis and breed complementarity into a herd with greater ease than the rotational crossbreeding systems described above.

Composites

Some of the first such animals are the American Breeds, or Brahman Derivatives. Perhaps there is no greater example of breed complementarity (breeding animals to adapt to a specific environment) and consequently of heterosis.

The American Gelbvieh Association, North American Limousin Foundation, and American Simmental Association are three breed associations that have

implemented new programs to introduce composites such as the Balancer, Lim-Flex, and SimAngus, respectively. There is no doubt that some of these programs have met with opposition from within the respective associations due to an ignorant stance that purebred animals are superior. I greatly admire those who have pushed, pulled, and prodded these programs through.

Crossbred females have proven to be very profitable and well accepted from a commercial standpoint. The use of crossbred bulls has not been accepted so easily. Some common fears have been the perception of larger amounts of variation within composite populations and the lower accuracy of EPDs of composite animals. In a study of three composite lines at MARC and their parental purebreds, there were no statistical significant differences in the coefficient of variation for reproduction, production, or carcass traits measured (Table 10).

Breed Complementarity

In addition to heterosis, crossbreeding programs can increase production efficiency by using additive (highly heritable) traits through *complementarity*. Differing breeds can be matched to complement traits, more closely fitting the genetic goals for biological type.

Complementarity is fully exploited under a system when crossbred cows of lower frame size, and optimum milk are crossed with a large framed terminal breed, noted for rapid growth and carcass leanness in order to produce market animals [11].

Simulation work by Lamb et al. [12] shows that generally English breeds are more biologically efficient, while Continental breeds are more economically

Breeding in Beef Cattle. Table 9 Maternal heterosis: Advantage of the crossbred cow

Trait	Observed improvement	% Heterosis
Calving rate	3.5	3.7
Survival to weaning	0.8	1.5
Birth weight	1.6	1.8
Weaning weight	18.0	3.9
Longevity	1.36	16.2
Cow lifetime production		
No. Calves	0.97	17.0
Cumulative weaning weight, lb.	600	25.3

Source: Adapted from Cundiff and Gregory [9]

Breeding in Beef Cattle. Table 10 Coefficients of variation for purebred versus composite steers

Trait	Purebreds	Composites
Birth weight	0.12	0.13
Wean weight	0.10	0.11
Carcass weight	0.08	0.09
Retail product %	0.04	0.06
Marbling	0.27	0.29
Shear force	0.22	0.21

Source: Adapted from [10]

efficient. The English X Continental cross was the most biologically and economically efficient. In some environments, heat and disease tolerance of the Brahman (*Bos Indicus*) may be required to complement the carcass traits, disposition, and age at puberty of an English breed [13].

Crossbreeding Systems

There are many other crossbreeding systems that vary significantly in terms of difficulty. Items that can influence the success of a crossbreeding system include:

1. Number of cows in the herd
2. Number of available breeding pastures
3. Labor and management
4. Production and marketing system
5. Availability of high-quality bulls of the various breeds

Terminal Cross All offspring from a terminal cross are sold. The sire used is usually from a breed noted for high growth, and desirable carcass end product. Under this system, genetic differences between maternal and terminal breeds can be exploited through complementarity. Individual heterosis is improved an additional 5% from this type of cross [11]. If female replacements are not generated, little emphasis needs to be placed upon milking genetics of the sires used. By purchasing crossbred F1 females, maximum maternal heterosis can also be achieved.

Two-Breed Terminal In this simple situation, cows of breed A are bred to bulls of breed B and all offspring are sold. In this system, the offspring are F1s and will benefit from 100% of the possible individual heterosis.

Three-Breed Terminal In this situation, cows that are F1 females comprised of $\frac{1}{2}$ breed A and $\frac{1}{2}$ breed B are mated to bulls of breed C for the production of terminal offspring. In this system, calves not only benefit from 100% of the possible individual heterosis, but maternal heterosis is realized as well. In general, the females should be a cross of two maternal breeds that emphasize efficiency and milking ability while the sire breed should inject growth.

Rotational Systems The three-breed rotation is similar to the two-breed rotation. A third breed is added to this system, thus a third breeding pasture is needed, unless AI is utilized. Management of this system is patterned after the two-breed rotation. If the maximum amount of heterosis is 23.3% (14.8% + 8.5%) then the expected level of heterosis is higher with a three-breed than two-breed rotation, 86% versus 67% [14].

Two-Breed Rotation A two-breed rotation is a simple crossbreeding system requiring two breeds and two breeding pastures. The two-breed rotational crossbreeding system is initiated by breeding cows of breed A to bulls of breed B. The resulting progeny (A*B) chosen as replacement females would then be mated to bulls of breed A for the duration of their lifetime. The service sire is the opposite breed of the female's own sire. These progeny are then one-quarter breed A and three-quarters breed B. Since these animals were sired by breed B bulls, they are mated to breed A bulls. Each succeeding generation of replacement females is mated to the opposite breed of their sire. Initially only one breed of sire is required. Following the second year of mating, two breeds of sire are required. After several generations, the amount of retained heterosis stabilizes at about 67% of the maximum heterosis, resulting in an expected 16% increase in the pounds of calf weaning weight per cow exposed above the average of the parent breeds [14]. In this system, a minimum of two breeding pastures and 50 cow units are required.

Three-Breed Rotation A three-breed rotational system achieves a higher level of retained heterosis than a two-breed rotational crossbreeding system does. After several generations, the amount of retained heterosis stabilizes at about 86% of the maximum heterosis, resulting in an expected 20% increase in the pounds of calf weaning weight per cow exposed above the average of the parent breeds [14]. Like the two-breed system, distinct groups of cows are formed and mated to bulls of the breed that represents the smallest fraction of the cows breed makeup. A cow will only be mated to a single breed of bull for her lifetime.

A minimum of three breeding pastures is required for a three-breed rotational system. Replacement females must be identified by breed of sire to ensure proper matings. The minimum herd size is approximately 75 cows with each one-third being serviced by

one bull of each breed. Scaling of herd size should be done in approximately 75 cow units to make the best use of service sires, assuming one bull per 25 cows. Replacement females are mated to herd bulls in this system, so extra caution is merited in sire selection for calving ease to minimize calving difficulty. The progeny produced from these matings that do not conform to the breed type of the herd should all be marketed. Breeds used in rotational systems should be of similar biological type to avoid large swings in progeny phenotype due to changes in breed composition. The breeds included have similar genetic potential for calving ease, mature weight and frame size, and lactation potential to prevent excessive variation in nutrient and management requirements of the herd.

When choosing a crossbreeding system it is critical to consider more than the amount of heterosis retained. After all, each system requires different levels of input (pastures, etc.) and differing levels of difficulty. Table 11 describes the advantages and requirements for the above mentioned crossbreeding systems.

Molecular Information

Molecular Information: Paternity and Simply Inherited Traits

Molecular-based tools are another source of information that has received considerable attention by

producers throughout the beef industry and by both the academic community and the private sector. These tools initially came in the form of candidate genes but have now grown to the inclusion of multiple markers called Single Nucleotide Polymorphisms (SNPs). The use of molecular information has grown from simple applications such as identifying animals that are carriers of the red allele to identifying animals that are carriers of lethal genetic defects, to paternity assignment, and a growing number of diagnostic tests for a suite of complex traits ranging from reproduction to carcass.

Genotyping to determine parentage allows for a sire to be correctly linked to a corresponding calf. The identification of an animal's sire via DNA marker technology can be advantageous in multi-sire breeding pastures, or for ascertaining if a calf is the product of an artificial insemination (AI) mating or a clean-up bull. This promotes knowledgeable culling and breeding decisions by determining which sire(s) are contributing the most (or least) to a particular breeding objective. In the case of commercial ranch settings, for example, it may be beneficial to determine the sire that is responsible for calving difficulties.

Because paternity identification is a process of excluding potential sires on the basis of their genotype, it is important that DNA from all possible sires be included in paternity tests. It will be more difficult to

Breeding in Beef Cattle. Table 11 Summary of crossbreeding systems by advantage and other factors

Type of system		Advantage ^a	Retained heterosis ^b	Minimum no. of breeding pastures	Minimum herd size	No. of breeds
2-breed rotation	A*B rotation	16	67	2	50	2
3-breed rotation	A*B*C rotation	20	86	3	75	3
Terminal cross with straightbred females ^c	T*A	8.5	0	1	Any	2
Terminal cross with purchased F1 females	T*(A*B)	24	100	1	Any	3
Rotating unrelated F1 bulls	A*B x A*B	12	50	1	Any	2
	A*B x A*C	16	67	1	Any	3
	A*B x C*D	19	83	1	Any	4

Source: Adapted from Ritchie et al. [14]

^aMeasured in percentage increase in lb of calf weaned per cow exposed

^bRelative to F1 with 100% heterosis

^cCundiff and Gregory [15]

definitively make paternity assignments on closely related bulls in a multiple-sire breeding pasture, given they are likely to share a similar genotype. Although microsatellites have typically been the marker of choice for paternity analysis, the use of SNP markers is becoming more common for a number of reasons including their abundance, high potential for automation, low genotyping error rates, and ease of standardization between laboratories.

Although identifying carriers of genetic defects is a rather simple application of DNA technology, it is an important tool when making mating decisions. It is known that afflicted animals can only arise if two carrier animals are mated. In this scenario, there exists a 25% chance that the corresponding calf will have the defect. Unfortunately, this added information has been used as the primary selection tool whereby carrier animals are automatically discarded. If a producer potentially has carrier females, then carrier bulls should be avoided. However, if this is not the case, then it could be beneficial to use the best available bull, regardless of his status as a carrier. As an industry, there is the ability to make informed decisions based on science concerning this issue and not throw away animals that are superior across the remainder of their genome because they have a flaw that can be effectively managed around.

Molecular Information: Complex Traits

Several advancements in molecular technology have occurred with regard to complex traits (i.e., production, carcass, and reproduction traits). Including the number of markers included in a given panel, reporting styles of the results, and the number of traits for which a diagnostic test exists. Recently, this information is included in the Angus National Cattle Evaluation (NCE) for the first time.

The promise of the inclusion of marker information into EPD calculations holds three primary benefits:

1. Increased accuracy for young animals (i.e., yearling bulls), which is particularly beneficial when selecting on traits that are measured late in life (e.g., stayability)
2. Shortened generation intervals

3. EPD values for novel traits (i.e., efficiency, end-product healthfulness, disease susceptibility) that may have, at best, sparse collection of phenotypes

However, the magnitude of these benefits will depend on the proportion of variation explained by a given marker panel. At present, the best objective source of information regarding this is the National Beef Cattle Evaluation Consortium (NBCEC) Web site (www.nbcec.org). Pertinent information from this Web site includes population, trait, regression coefficient (b), and the p-value (p). The population defines what breed(s) were used to validate the test. If the test was validated in *Bos taurus* animals then it is possible that the test will not explain the same proportion of variation in *Bos indicus* animals. The trait defines what the test was validated for. If it is a metric of efficiency like residual feed intake (RFI) then it will explain how the trait is defined. Generally, a p-value of less than 0.05 suggests that the test is a statistically significant predictor of differences in phenotypes. The regression coefficient is equal to the regression of phenotypes for the trait of interest on the molecular score. It explains the units of change in the phenotype that would be expected for a one-unit change in the molecular score (i.e., MBV). Ideally, these b values should be 1. For example, if two animals have molecular scores for RFI of -1.5 and 1.0 , respectfully, the difference between those scores is 2.5 . Normally it is expected that, on average, these two animals' phenotypes would differ by 2.5 lb of RFI. However, if the regression coefficient is 0.4 then their phenotypes are expected to differ by 1 lb (2.5×0.4).

Without the seamless integration of this technology into EPD calculations, the industry is faced with two disjointed pieces of information: traditional EPD and marker panel results. In this scenario, it is impossible to directly compare EPD to marker panel results even if the results come in the form of molecular breeding values (MBVs). This is because the molecular scores only explain a portion of the additive genetic variation. Further, some of the marker panel results have a metric of accuracy associated with them. At the current time, this metric is not comparable to the Beef Improvement Federation accuracy value associated with EPD simply due to differences in the way they are computed. While it is logical that the accuracy value of a MBV should be related to the proportion of additive genetic variation

explained by the test there is not a standardized metric that is being used. Thallman et al. [16] analyzed different methods of calculating this proportion for MBV in light of the fact that there is not a standardized method and recommended the use of the square of the additive genetic correlation between the MBV and the trait of interest.

In contrast to the thought process of DNA marker panel results being a separate and disjointed piece of information, these test results should be thought of as a potentially useful indicator that is correlated to the trait of interest. As such, the MBV can be included in NCE as a correlated trait following methods of Kachman [17]. Other methods have been proposed including using large (50,000 +) SNP panels to form a genomic relationship matrix that could allow for known relationships between animals based on genotypes across SNP loci. Combining these sources of information, molecular tools and traditional EPDs, has the potential to allow for the benefits of increased accuracy and increased rate of genetic change as discussed earlier.

MacNeil et al. [18] utilized Angus field data to look at the potential benefits of including both ultrasound records and MBVs for marbling as correlated traits in the evaluation of carcass marbling score. MacNeil and colleagues used a 114 SNP marker panel that was developed using 445 Angus animals and calculated to have a genetic correlation (r) of 0.37 with marbling (i.e., the test explained $(0.37)^2 = 0.137$, or 13.7%, of the additive genetic variation). For animals with no ultrasound record or progeny data, the marker information improved the BIF accuracy of the Angus marbling EPD from 0.07 to 0.13. Assuming a heritability of 0.3 for marbling, a BIF accuracy of 0.13 is equivalent to having approximately 5 progeny carcass records on a young animal or an ultrasound record on the individual itself. In this particular study, both ultrasound records and MBV were found to be beneficial indicators of carcass marbling. The genetic correlation between MBV and ultrasound was found to be 0.80. Some breeds have begun to integrate this technology and it is likely that more will do so in the future.

Considerations

Current marker panels are likely to work best in the populations where discovery occurred, but will

potentially decrease in predictive power as the target population becomes more genetically distant from the discovery population [19]. Below is an example of scenarios where the discovery population is close to the target population and progresses to more distant populations.

Discovery	Target	
Angus	Angus	Closest relationship
Angus	Charolais	
Angus	<i>Bos indicus</i>	Most distant relationship

Marker panels are likely to become larger in the future with the possibility of whole genome selection (WGS). Currently, genome selection in beef cattle is in its infancy. Although preliminary data from the dairy industry look promising [20], the structure of the beef industry offers unique challenges. It is not known how well this approach will work in beef cattle with its diversity of breeds, diverse sector-specific selection goals, and less extensive phenotype and data collection resources.

Future Directions

Undoubtedly, molecular discoveries and their seamless integration into existing infrastructures and genetic selection tools will aid in the increased rate of genetic change and hopefully profitability of producers. These molecular tools will be in the form of larger (770 K) SNP panels and genome sequences. At the same time, a suite of reduced marker panels will be commercialized for use on progeny while the larger panels are used for herd bulls. These molecular tools will be integrated into breeding value estimations allowing for higher accuracy values on younger animals and allowing for genetic predictions of traits that have not yet been exploited such as the nutrient content of beef, feed efficiency, and susceptibility to disease. Effort will also be placed on precision mating, or specific combining ability, when developing composite animals, aided by molecular technology. One final area of effort includes the robustness of marker effects across breeds and environments, and how to accommodate these differences in national cattle evaluations. All of this has the potential to allow for selection on total profitability and not just production, ultimately aiding in the sustainability of the beef industry worldwide.

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Breeding in Developing Countries and Tropics

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Article Outline

Glossary
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Introduction
Setting the Scene
Animal Resources
The Most Important Livestock Products for Ensuring Food Security
Challenges
The Technological Age
Future Directions
Conclusion and Recommendations
Bibliography

Glossary

- Fitness** A measure of the ability of an organism to survive and reproduce in a particular environment.
- Genetic resource** Genetic material of plants or animals of value as a resource for future generations of humanity.
- Genomics** The study of the genomes of organisms, including intensive efforts to determine the entire DNA sequence of organisms as well as fine-scale genetic mapping.
- Phenotype** The appearance of an organism based on an interactive combination of genetic traits and environmental factors.
- Selection** Choosing organisms with desirable genetic characteristics for propagation from candidates available.
- Sustainability** The capacity to endure, that is, the ability of biological systems to remain diverse and productive over time.

Definition of the Subject and Its Importance

Species breeding has led to marked genetic improvement of production by livestock in the developed world over the past decades. Selection has been so successful that the emphasis in the breeding objective has been changed to welfare, behavior, and other consumer-orientated objectives. The same level of progress has not been achieved in the developing world. Current and projected future population growth requires that food production from farm animals in these regions be improved markedly from the present inadequate levels. Limitations in the institutional infrastructure and the unique challenges of livestock production in the emerging world and the tropics were discussed in detail. This led to recommendations on how these challenges can be overcome and how “new” issues like global warming and animal welfare should be handled in a sustainable manner. Focus should be on the phenotyping of individuals for production and particularly for traits associated with fitness. Data should be linked to pedigree information where possible, to generate a broad-based institutional environment where the genetic improvement of animals in the developing countries can be strived for. Samples for the acquisition of DNA should be obtained from phenotyped individuals, for possible later genomic studies. Continued

further learning and the accrual of information as well as collaboration to mutual benefit across institutional and national boundaries are needed to enable this. Sustainable livestock improvement in the developing world could accrue if these prerequisites are met.

Introduction

It is fair to say that the past decades have been marked by rapid change. Mankind had to adapt to immense technological progress, rapid urbanization, instability on monetary markets, as well as becoming part of the global village. The changes listed above are by no means exhaustive and many other challenges to the current generation can also be noted.

Yet it is important to note that there is still immense poverty in parts of the world, despite groundbreaking scientific breakthroughs as well as rapid progress in communication systems allowing easy access to the information that are generated elsewhere in the global village. While the developed world appears to be going from strength to strength in the acquisition and application of knowledge, the developing countries are lagging behind. In the Millennium Development Goals Report [1], Kofi Annan (the then secretary general of the United Nations) stated: “We will not enjoy development without security, we will not enjoy security without development, and we will not allow either without respect for human rights. Unless all these causes are advanced, none will succeed.”

As a point of departure it has to be observed that the fundamental human rights of millions of people in the developing world are closely interwoven with livestock and the meat, milk, or fiber they produce [2–5]. The livestock industry is inextricably linked with the eradication of extreme poverty and hunger (Goal 1) and the ensuring of environmental sustainability (Goal 7) [1]. Improved and sustainable levels of animal production could not only contribute to improved household food security, but also to an increased household income in the developing world. This could lead to spinoffs indirectly benefitting other millennium development goals, such as the achievement of universal primary education (Goal 2), the reduction of infant mortality (Goal 4), and an improved maternal health (Goal 5). The benefits of including meat in diets of vulnerable groups are becoming evident now [6, 7].

During an exercise where livestock and poverty in the developing world were mapped by Thornton et al. [4] it became evident that large areas of the developing countries are only fit for rangeland-based livestock production. Considerable other areas are also utilized by livestock in combination with cropping in rainfed or irrigated mixed production systems. Ruminant livestock strongly depends on crop residues and the intercrops planted in the ley-farming systems which are preferred at present [8].

Against this background, it is reasonable to assess the contribution of livestock breeding to the sustainability of livestock production systems. This topic is addressed by providing background information leading to thoughts on global food security, information pertaining to farm animal genetic resources and livestock products contributing to food security, and external and internal challenges, the advent of the technological age and challenges stemming from it. These topics culminate in proposed future directions to place sustainable farm animal breeding in the developing world and the tropics on a solid foundation, before some concluding remarks.

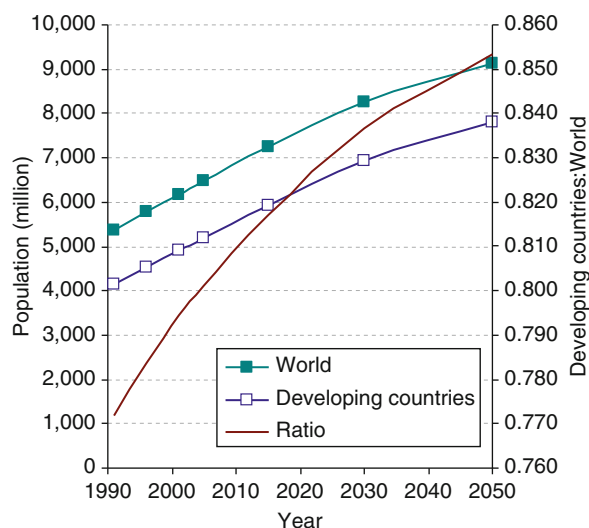
Setting the Scene

World Population

The world population grew steadily from 1990–1992 to 2004–2006 (Fig. 1). Extrapolation beyond the data to 2050 suggests sustained population growth from 5,358 million people in 1990–1992 to 9,136 million people in 2050, an increase of 71%. In the case of the developing world, this increase amounts to 89%, from 4,135 million people in 1990–1992 to 7,797 million people in 2050. Expressed as a ratio, 0.77 of people were living in the developing world in 1990–1992, compared to an estimated 0.85 in 2050. The impact of this change of population structure on the available resources in terms of plant and animal production is evident.

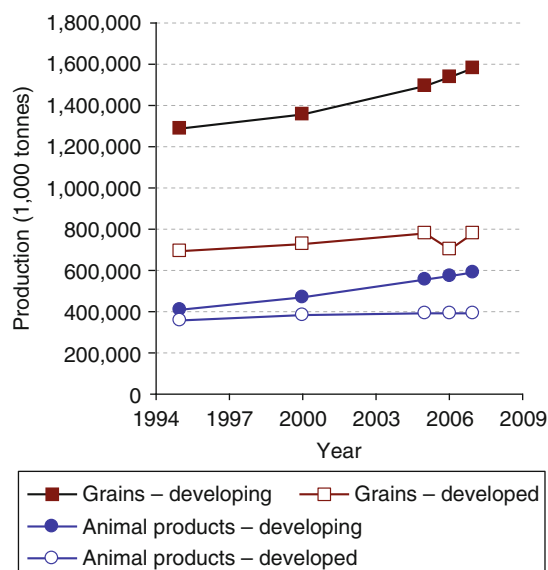
Global Food Production

Given the increase in the global population and the even faster population growth in the developing countries, it is imperative to have a look at global food production. The production of grain in the developing world has increased from ~1.3 million kilotons in 1995 to just below 1.6 million kilotons in 2007 (Fig. 2).



Breeding in Developing Countries and Tropics. Figure 1

The population growth of the developing countries relative to the entire human population of the world from 1990–1992 to 2004–2006, and extrapolated beyond that to 2050. The human population in the developing countries is also expressed as a ratio of the world population (Source: FAO [9])



Breeding in Developing Countries and Tropics. Figure 2

The production of grains and animal products (meat, milk, and eggs) in countries of the developing world and the developed world (Source: FAO [10])

Expressed relative to 1995 production, this increase amounted to 23%. Grain production in the developed world amounted to just below 0.69 million kilotons in 1995 and 0.78 million kilotons in 2007, an increase of about 12%. Animal products (meat, milk, and eggs) in the developing world increased from 0.41 million kilotons in 1995 to 0.59 million kilotons in 2007, an increase of 44%. Animal products in the developed

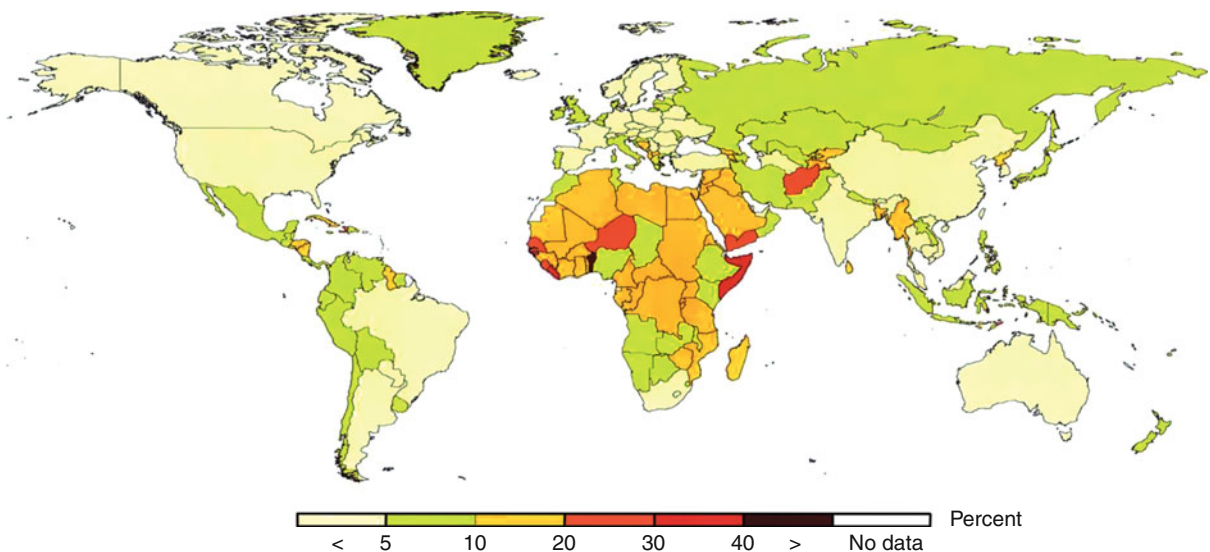
world, in contrast, remained fairly stable at between 0.36 and 0.40 million kilotons over the entire period. There thus seems to be an effort on the part of the developing world to compensate for the faster population growth by a higher food production. However, this increase has to be seen in relation to the relative size of the respective populations in the developing and developed countries. Grain production per head of the developed world increased by 8.5% from 563 kg/head in 1995 to 611 kg/head in 2005 (Table 1). Grain production per head in the developing world, in contrast, remained relatively stable at a substantially lower level of between 275 (during 2000) and 286 (during 2005) kg/head (a difference of 4.0%). The output of animal products accordingly ranged from 293 to 308 kg/head in the developed world, compared to between 90 and 107 kg/head in the developing world.

The lower per capita production of food in the developing world results in the need for imports to contribute to the food supply of the local population. The global importation of food in relation to total imports is provided in Fig. 3. It is evident that food imports exceed 5% of overall imports in many countries in the developing world. Africa and the Middle East are particularly dependent upon imports of food to contribute to local food security, with food imports

Breeding in Developing Countries and Tropics. Table 1
Per capita production of grain and animal products (meat, milk, and eggs) in developing and developed countries during 1995, 2000, and 2005

Product type and regions	Year		
	1995	2000	2005
Grains			
Developing regions	281.9	275.4	286.0
Developed regions	563.1	582.8	611.3
Livestock products			
Developing regions	90.4	95.0	107.4
Developed regions	293.4	306.5	308.2

Source: FAO [10].



Breeding in Developing Countries and Tropics. Figure 3

The share of food imports in relation to total imports on a global basis (Source: FAO [10])

exceeding 10% of total imports in most countries. On the upper end of the scale, food imports contribute more than 30% to total imports in some countries in these regions.

Products of an Animal Origin

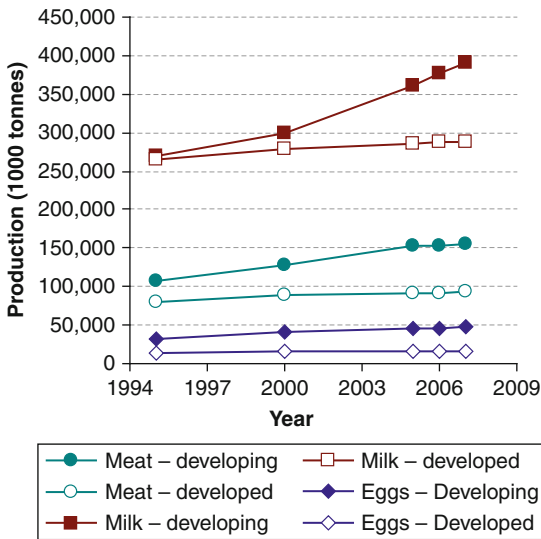
Table 1 suggests substantial differences between the developing world and the developed world in terms of per capita animal production. As this entry deals with animal products, this topic needs to be elucidated further. In terms of quantity, milk was the most important animal product, followed by meat and eggs (Fig. 4).

The same ranking applied both in developing and developed countries. It is evident that the production of all livestock products increased substantially over the past decade in the developing world (Fig. 4). Production in the developed world, on the other hand, remained stagnant or increased by smaller increments. These trends are set to continue in the future [11]. However, it needs to be considered that the population of the developing world exceeded 80% of the global population during 2005. It is thus evident that the somewhat higher animal production in these regions

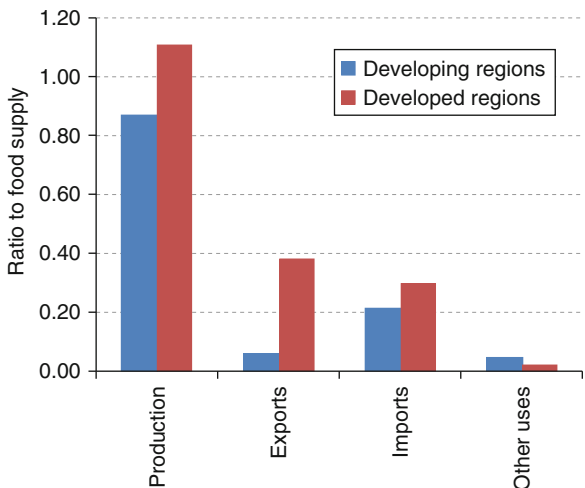
is canceled by the larger population density, hence the almost threefold lower per capita output of animal products in Table 1.

Against this background, local meat production is balanced against overall food supply for this commodity in developing countries and developed countries in Fig. 5. It is seen that there is a clear deficit in local production in the developing countries, as opposed to an oversupply in the developed countries. The deficit in own production in the developing countries is negated by imports, while only a small proportion of meat is exported. Developed countries are more likely to export meat, but also import relatively more meat than developing countries. The proportion of meat affected by stock changes and other purposes (mostly cultural) is relatively small, but appears to be somewhat higher in developing countries.

Table 1 suggests a substantially lower per capita production of animal products in developing countries relative to developed countries. In Fig. 6, this tendency is quantified for the top ten animal products globally. Per capita energy consumption from small stock (sheep and goat) meat in the developing regions amounted to 79% of that in the developed world. Other products where per capita energy consumption of the developing



Breeding in Developing Countries and Tropics. Figure 4 Relative quantities of the most important livestock products in developing and developed countries (Source: FAO [10])

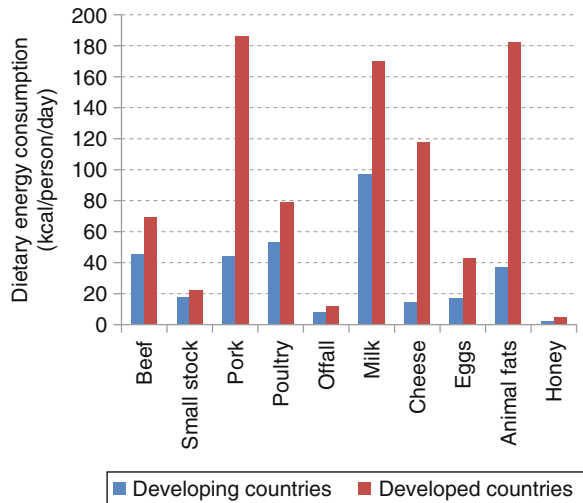


Breeding in Developing Countries and Tropics. Figure 5 A food balance for animal meats for the developing world and the developed world relative to the overall food supply in kiloton (Source: FAO [10])

world exceeded 50% of the corresponding figure in the developed world are poultry (67%), offal (67%), beef (65%), and milk (57%). Inhabitants of the developing world consumed energy from eggs (39%), honey

(38%), pork (24%), animal fats (21%), and cheese (12%) at much lower quantities than their counterparts in the developed world.

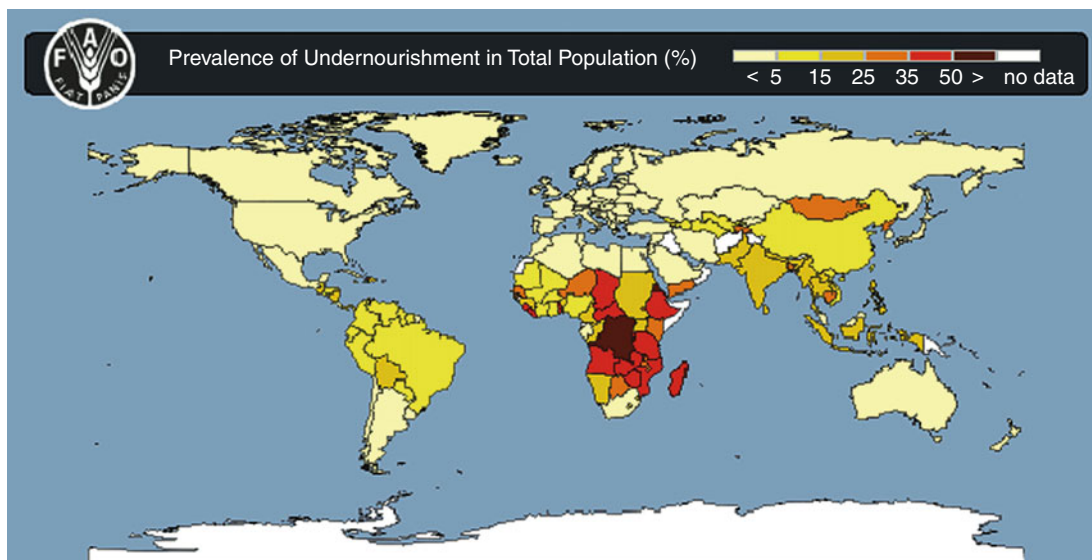
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Breeding in Developing Countries and Tropics. Figure 6
Per capita energy consumption of the top ten animal products in the developing world and in the developed world (Source: FAO [10])

Global Food Security

It is evident from Fig. 6 that inhabitants of the developing world consume substantially less energy from animal products than their counterparts in the developed world. It is thus important to consider relative food security of both groupings in view of these results. It is estimated that ~854 million people in the world lack adequate nourishment for a healthy and productive lifestyle, a figure that remained fairly stable over the last two decades [9]. The number of people dependent on one or other form of food aid for a livelihood is estimated at ~73 million worldwide. It is notable that the most insecure areas in terms of the provision of food are in developing countries in Asia and the Pacific, Latin America and the Caribbean, and Near East and Sub-Saharan Africa. Figure 7 depicts the frequency of undernourishment in different areas of the world as a percentage of the total population. It is evident that people in the central part of Africa are particularly at risk from undernourishment, but that variable levels of



Breeding in Developing Countries and Tropics. Figure 7

The prevalence of undernourished people as a percentage of the total population in different countries throughout the world (Source: FAO [9])

undernourishment also occurs in South and Central America, in South and central Asia, and in Oceania.

The percentage of undernourished people worldwide was estimated at 16% in 1990–1992, 14% in 1995–1997, 14% in 2002–2004, and at 13% in 2004–2006 [10]. It is notable that less than 5% of the total population suffered from undernourishment in the developed world. Less than 5% of the population of the developing states in Northern Africa correspondingly suffers from undernourishment. The occurrence of undernourishment is compared for other regions in the developing world over time from 1990–1992 to 2004–2006 in Fig. 8.

It is notable that most regions reported a slight decline in food insecurity, but that it still remains at unacceptably high levels. Sub-Saharan Africa and Southern Asia were the regions where the population was most at risk during recent years (Fig. 8).

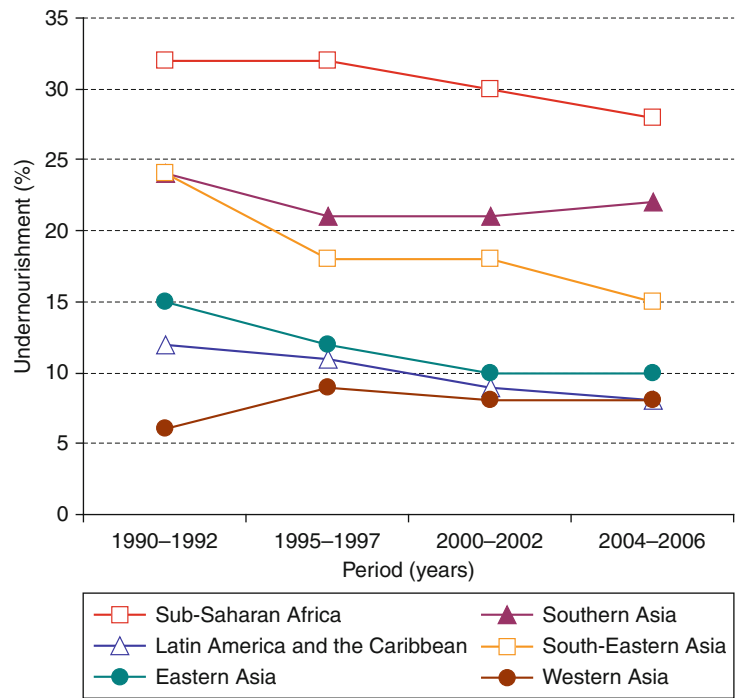
So far the discussion has centered around trends in the global human population, livestock products, as

well as the issue of food security. The animal resources at the disposal of the global community for the alleviation of food insecurity need to be considered next.

Animal Resources

Domestication

Present-day production systems depend on Livestock species domesticated in the distant past. Fifteen out of 148 non-carnivorous species weighing more than 45 kg were domesticated, while only 10 out of an estimated 10,000 avian species were domesticated [12]. The time lapses since domestication of mammal livestock (in ascending order) is estimated at 10,000 years for goats, 8,500 years for sheep, 7,000–9,500 years for cattle, 6,500 years for horses and the South American camelids, 6,000 years for donkeys, 4,500–5,000 years for camels, 4,500 years for yaks and 4,000–4,500 years for water buffalo [12]. Chickens were domesticated between 5,000 and 7,500 years ago.



Breeding in Developing Countries and Tropics. Figure 8

The frequency of undernourishment in regions within the developing world over time from 1990–1992 to 2004–2006 (Source: FAO [9])

Distribution of Livestock Domestication, the resultant controlled breeding and selection, and the dispersal of domesticated livestock by human migration resulted in a wealth of diverse animal genetic resources. These livestock species are widely dispersed and adapted to a wide variety of environments and production systems. The percentages of countries in regions throughout the world that reported the presence of a specific domesticated mammalian species are listed in Table 2.

The wide representation across countries among the mammalian livestock species traditionally used for food production (cattle, sheep, goats, and pigs) is evident from Table 2. The exceptions are sheep that are somewhat underrepresented in the Southwest Pacific at 31%, and pigs that are underrepresented in the Near and Middle East at 8%. Species like buffaloes, rabbits, and deer are important contributors to food security in some regions. Other species (yaks, camels, South

American camelids, and guinea pigs) also contribute to regional food security, but are extremely localized in their distribution.

Domestic chickens are the most important avian livestock species by far (Table 3). Livestock species like turkeys, ducks, geese, Muscovy ducks, pigeons, quails, and guinea fowl also contribute in most regions of the world, but are nowhere close to the role played by domestic chickens. Other species (partridges, pheasants, peacocks, and the ratite species) also contribute to regional food security, but are fairly to extremely localized in their distribution.

At ~1.35 billion head, cattle have to be considered as the most important mammalian livestock species in the World (Table 4). Cattle are closely followed by sheep (1.08 billion head), pigs (0.96 billion head), and goats (0.81 billion head). The only other species exceeding half a billion head are rabbits at 0.54 billion head. Regions housing more than 10% of the world

Breeding in Developing Countries and Tropics. Table 2 The percentage of countries in different regions of the world reporting the presence of specific mammalian livestock species

Mammalian species	Region						
	Africa	Asia	Europe and the Caucasus	Latin America and the Caribbean	Near and Middle East	North America	Southwest Pacific
Cattle	98	96	100	94	75	100	77
Sheep	92	86	100	91	100	100	31
Goats	96	96	93	94	83	100	69
Pigs	70	82	91	91	8	100	92
Horses	46	93	91	64	58	100	23
Donkeys	38	46	36	39	50	50	–
Buffalo	8	57	25	27	25	0	0
Deer	2	25	14	9	0	50	15
Rabbit	38	39	39	48	8	0	0
Dromedary	32	25	2	0	58	0	8
Bactrian camel	0	25	5	0	0	0	0
Yak	0	32	2	0	0	0	0
Guinea pig	8	0	0	15	0	0	0
Alpaca	2	0	0	12	0	0	0
Llama	0	0	0	15	0	0	0
Vicuña	0	0	0	12	0	0	0

Source: Adapted from Rischkowsky et al. [13].

Breeding in Developing Countries and Tropics. Table 3 The percentage of countries in different regions of the world reporting the presence of specific avian livestock species

Avian species	Region						
	Africa	Asia	Europe and the Caucasus	Latin America and the Caribbean	Near and Middle East	North America	Southwest Pacific
Chicken	78	93	86	70	50	100	85
Turkeys	24	43	57	30	17	100	8
Ducks	32	61	50	33	17	0	46
Geese	16	39	61	21	17	50	8
Muscovy ducks	16	39	20	18	17	0	62
Guinea fowl	28	18	11	9	8	0	0
Pigeons	10	21	9	6	17	0	15
Quails	2	39	14	6	0	50	0
Partridges	4	7	7	0	0	0	0
Pheasants	0	7	9	6	0	0	0
Ostriches	12	11	7	0	0	0	8
Emus	2	4	2	3	0	0	0
Cassowary	0	4	2	0	0	0	0
Peacocks	0	0	0	2	0	0	0

Source: Adapted from Rischkowsky et al. [13].

Breeding in Developing Countries and Tropics. Table 4 The world's population of the most important mammalian livestock species, with the relative contribution of the different world regions as percentages

Species	Region							World population (billion head)
	Africa (%)	Asia (%)	Europe and the Caucasus (%)	Latin America and the Caribbean (%)	Near and Middle East (%)	North America (%)	Southwest Pacific (%)	
Cattle	14	32	11	28	3	8	3	1.355
Sheep	16	36	18	7	9	1	14	1.081
Pigs	2	62	20	8	0	8	0	0.960
Goats	22	62	4	4	8	0	0	0.808
Rabbits	0	74	24	1	2	0	0	0.537
Buffalo	0	97	0	1	2	0	0	0.174
Horse	6	25	13	44	0	11	1	0.055
Donkeys	27	38	4	20	12	0	0	0.041
Camels	40	20	2	0	38	0	0	0.019
Camelids	0	0	0	100	0	0	0	0.006

Source: Adapted from Rischkowsky et al. [13].

cattle population are Asia (32%), Latin America and the Caribbean (28%), Africa (14%), and Europe and the Caucasus (11%). Sheep are mostly found in Asia (36%), Europe and the Caucasus (18%), and Africa (16%). Asia (62%) and Europe and the Caucasus (20%) house the majority of the global pig population, while the most important goat-rearing regions are Asia (62%) and Africa (22%). Rabbits are mostly found in Asia (74%) and Europe and the Caucasus (24%). Most of the world's camels are found in Africa (40%), the Near and Middle East (38%), and Asia (20%). [Table 4](#) confirms the status of buffaloes and South American camelids as truly regional livestock species.

Domestic chickens are by far the most important avian livestock species, with a more than tenfold advantage above ducks in the second place ([Table 5](#)). Most chickens are found in Asia (48%), while Latin America and the Caribbean (15%), Europe and the Caucasus (14%), and North America (13%) also house more than 10% of the world population.

Turkeys are found in Europe and the Caucasus (43%), North America (33%), and Latin America and the Caribbean (18%). Ducks and geese are almost exclusively found in Asia, where 90% of the world population can be found for both species.

It is also notable that most livestock can be found in the developing countries of Asia, the only exceptions being horses, camels, camelids, and turkeys ([Tables 4](#) and [5](#)). This is not surprising, given the high population density in this region, and the need for food produced by mammalian and avian farm animal genetic resources.

Biodiversity as Reflected by Breed Animal biodiversity is also illustrated by the number of distinct breeds that are identifiable in domestic livestock. The mammalian livestock species with the highest number of distinct breeds is sheep, followed by cattle, horses, pigs, goats, and rabbits ([Table 6](#)).

About half of the sheep breeds are found in Europe and the Caucasus, a quarter in Asia and about 12% in Africa. Regions with more than 10% of the cattle breeds are Europe and the Caucasus (31%), Asia (26%), Africa (19%), and Latin America and the Caribbean (14%). Most pig breeds are found in Asia (41%), followed by Europe and the Caucasus (32%), and Latin America and the Caribbean (12%). The regions with the most goat breeds are Asia (35%), Europe and the Caucasus (33%), and Africa (18%). Domestic chickens are the most diverse avian livestock species in terms of breed, with nearly five times as many distinct breeds than ducks in the second place ([Table 7](#)). Most chicken breeds are found in Europe and the Caucasus (58%) and Asia (22%). None of the other regions had more than 10% of the chicken breeds of the world. Regions with more than 10% of the world's duck breeds are Asia (38%), Europe and the Caucasus (36%), and Latin America and the Caribbean (11%). Goose breeds mostly originate from Europe and the Caucasus (65%) and Asia (24%). Most turkey breeds are found in Europe and the Caucasus (42%), with Africa, Asia, Latin America and the Caribbean, as well as North America all contributing 13% to the global animal diversity in terms of breeds. The contribution of Europe and the Caucasus to biodiversity, as reflected by distinct

Breeding in Developing Countries and Tropics. Table 5 The world's population of the most important avian livestock species, with the relative contribution of the different world regions as percentages

Species	Region							World population (billion head)
	Africa (%)	Asia (%)	Europe and the Caucasus (%)	Latin America and the Caribbean (%)	Near and Middle East (%)	North America (%)	Southwest Pacific (%)	
Chicken	6	48	14	15	3	13	1	16.740
Duck	1	90	7	2	1	1	0	1.046
Turkey	3	1	43	18	1	33	1	0.280
Geese	1	90	6	0	3	0	0	0.302

Source: Adapted from Rischkowsky et al. [[13](#)].

Breeding in Developing Countries and Tropics. Table 6 The biodiversity, as reflected by distinct breeds, of the most important mammalian livestock species, with the relative contribution of the different world regions as percentages

Species	Region							Number of breeds
	Africa (%)	Asia (%)	Europe and the Caucasus (%)	Latin America and the Caribbean (%)	Near and Middle East (%)	North America (%)	Southwest Pacific (%)	
Sheep	12	25	48	4	5	3	3	1,129
Cattle	19	26	31	14	4	3	3	990
Horses	7	24	48	11	2	4	4	633
Pigs	9	41	32	12	0	3	2	566
Goats	18	35	33	5	6	1	2	559
Rabbits	7	8	76	7	2	0	0	207
Donkeys	14	28	28	15	11	3	2	150
Buffalo	2	73	9	9	6	0	2	132
Camels	47	24	3	0	24	0	2	97
Camelids	0	0	0	100	0	0	0	13

Source: Adapted from Rischkowsky et al. [13].

Breeding in Developing Countries and Tropics. Table 7 The biodiversity, as reflected by distinct breeds, of the most important mammalian livestock species, with the relative contribution of the different world regions as percentages

Species	Region							World Population (billion head)
	Africa (%)	Asia (%)	Europe and the Caucasus (%)	Latin America and the Caribbean (%)	Near and Middle East (%)	North America (%)	Southwest Pacific (%)	
Chicken	8	22	58	8	2	1	2	1,132
Ducks	9	38	36	11	2	0	0	234
Geese	6	24	65	3	1	0	1	166
Turkeys	13	13	42	13	4	13	2	85

Source: Adapted from Rischkowsky et al. [13].

breeds, is higher than suggested by the contribution of this region to the overall livestock populations (Tables 4 and 5). The only exception in this respect is the turkey, where the contribution of the region to the population size and the number of breeds are roughly equal. It has been suggested that many of the breeds in this region are recognized as separate entities, while being quite similar genetically [13]. In contrast, breed recording and characterization may be constrained by

technical and human resources in parts of the developing world, such as Sub-Saharan Africa. This topic will be addressed later.

The Most Important Livestock Products for Ensuring Food Security

From the foregoing, it is possible to rank the domestic livestock species in terms of their importance to human food security, based on their population size and breed

diversity. There is little doubt that chickens, cattle, pigs, sheep, and goats need to be regarded as the most important livestock species in this context. More attention will thus be given to these species in the subsequent text. The importance of other regional species also needs to be considered. However, this would involve substantial additional information, which cannot be accommodated within the constraints of the present study.

Meat products are seen as important dietary sources of protein, iron, zinc, and vitamin b12 among others [7]. Meat products were related to increased live weight gains and improved cognitive function in children [14]. Meat thus has to be considered as an extremely important product for both the developed world and the developing world. Milk also provides calcium, phosphorus, vitamin B12, desirable fatty acids, and good-quality protein, and was also reported to have similar benefits to live weight and height of children under conditions where food supply is marginal [14]. The outlook for animal products (meat and dairy products) is subsequently provided per species for the major species listed above.

Meat from avian origin in this section is termed as poultry meat. However, with domestic chickens constituting more than 90% of avian livestock in the world (Table 5), it is safe to assume that the trends would also hold true for this species. Data were obtained from the

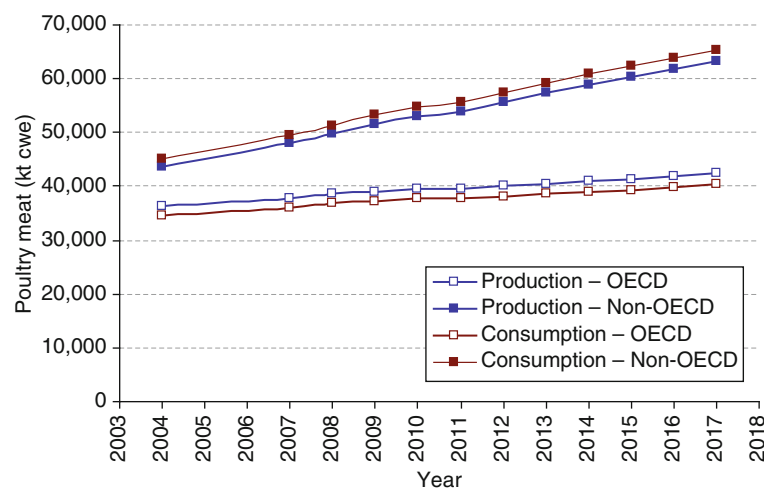
outlook document of the OECD-FAO [11], and the results are provided for OECD-member states (representing the developed world) and non-OECD countries (representing the developing world). After considering production and consumption figures per species, attention is focused upon the per capita consumption of the various species meats.

Poultry

Poultry meat production in the non-OECD countries is forecast to increase steadily by 45% from ~43,600 kt carcass weight equivalent (cwe) in the early 2000s to ~63,300 kt cwe in 2017 (Fig. 9). The corresponding increase in the OECD countries is forecast to be more modest, namely, an increase of 17% from ~26,400 to ~42,400 kt cwe. Poultry consumption, on the other hand, is seen to increase by 17% from ~34,600 to ~40,400 kt cwe in OECD countries, while the concomitant increase in non-OECD countries is expected to amount to 45% (from 45,100 to 65,300 kt cwe). A deficit in non-OECD countries is evident from Fig. 9, which can be partly offset by a surplus in production in the OECD countries.

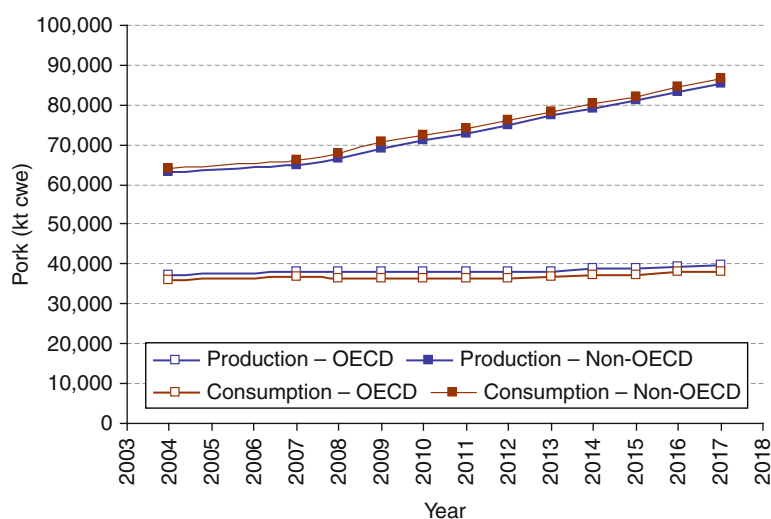
Pigs

The production of pork is expected to increase from ~63,200 kt cwe in 2004 to ~85,500 kt cwe in 2017 in



Breeding in Developing Countries and Tropics. Figure 9

Poultry meat production and consumption in kiloton carcass weight equivalent (cwe) in OECD and non-OECD countries (Source: OECD-FAO [11])



Breeding in Developing Countries and Tropics. Figure 10

Pig meat production and consumption in kiloton carcass weight equivalent (cwe) in OECD and non-OECD countries (Source: OECD-FAO [11])

the non-OECD countries, an increase of 35% (Fig. 10). OECD countries are likely to record a comparatively small increase, from ~37,100 to ~39,800 kt cwe. This increase only amounts to 7%. Consumption in the non-OECD countries is seen to increase by 36% from 63,900 to 86,900 kt cwe, while a modest increase of 7% was predicted for OECD countries (~35,800 to ~38,200 kt cwe). As for poultry meat, it was noted that a slight overproduction in OECD countries can once again be of value to counter a deficit in the non-OECD countries.

Cattle

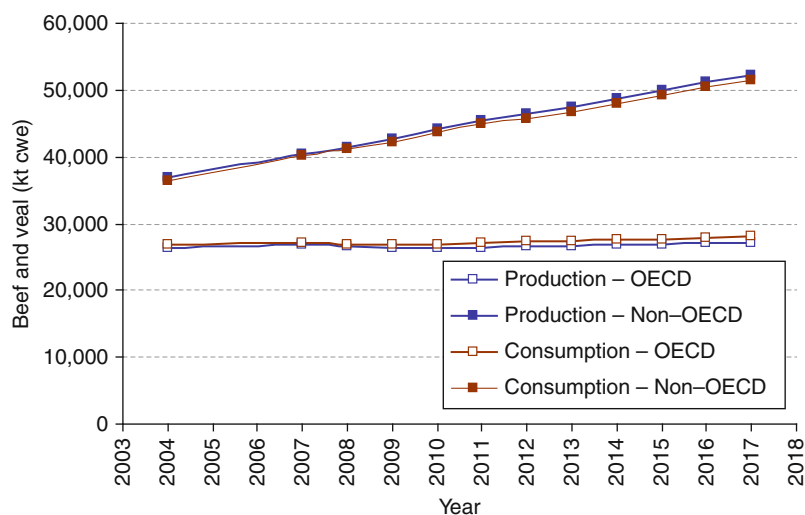
Beef and veal production is expected to increase by 41% in the non-OECD countries, from ~37,000 kt cwe in 2004 to 52,200 kt cwe in 2017 (Fig. 11). In contrast, production in OECD countries is forecast to be relatively stable at between 26,500 and 27,200 kt cwe. As with production, consumption of beef and veal in the non-OECD region is expected to increase by 41%, from 36,500 to 51,500 kt cwe over the period from 2004 to 2017. A slight increase of about 5% is expected in the consumption of beef and veal in the OECD countries (from 26,800 to 28,000 kt

cwe). Production and consumption seem to be in closer correspondence in both regions for this commodity.

Small Stock

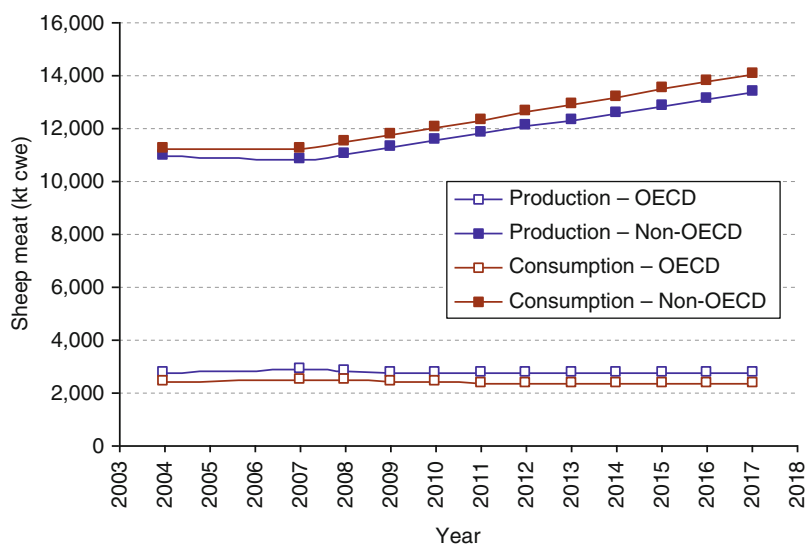
Global production of sheep meat (mutton and lamb) is modest compared to the other types of meat. Production in non-OECD countries is expected to increase by 22% from ~10,900 kt cwe in 2004 to ~13,500 kt cwe in 2017 (Fig. 12). No increase in sheep meat production is forecast for OECD countries, and figures are expected to remain stable at 2,300–2,400 kt cwe over the entire period. Consumption of sheep meat is expected to increase by 25% in non-OECD countries (from ~11,300 to ~14,100 kt cwe), while sheep meat consumption is expected to decline by 3% in OECD countries (from 2,417 to 2,340 kt cwe). As for other meats, surplus production of sheep meat in the OECD countries may play a role in alleviating the deficit expected in non-OECD countries.

Global goat meat (chevron) production all but doubled from 2.05 million ton in 1985 to 4.05 million ton in 2005 [15]. This trend could mostly be ascribed to a 2.5-fold increase in goat meat production from 1.3 million ton in 1985 to 3.3 million ton in 2005 in



Breeding in Developing Countries and Tropics. Figure 11

Beef and veal production and consumption in kiloton carcass weight equivalent (cwe) in OECD and non-OECD countries (Source: OECD-FAO [11])



Breeding in Developing Countries and Tropics. Figure 12

Sheep meat production and consumption in kiloton carcass weight equivalent (cwe) in OECD and non-OECD countries (Source: OECD-FAO [11])

Asia. Less spectacular increases from 1985 to 2005 were reported for other countries in the developing world, namely, from 0.53 to 0.86 kt in Africa and from 0.59 to 0.83 kt in South America. In the developed world,

Europe led the way with a 33% increase in chevron production from 0.09 to 0.12 kt. In contrast, goat meat production in Oceania declined markedly from 0.12 kt in 1985 to 0.02 kt in 2005 [15].

Per Capita Meat Consumption

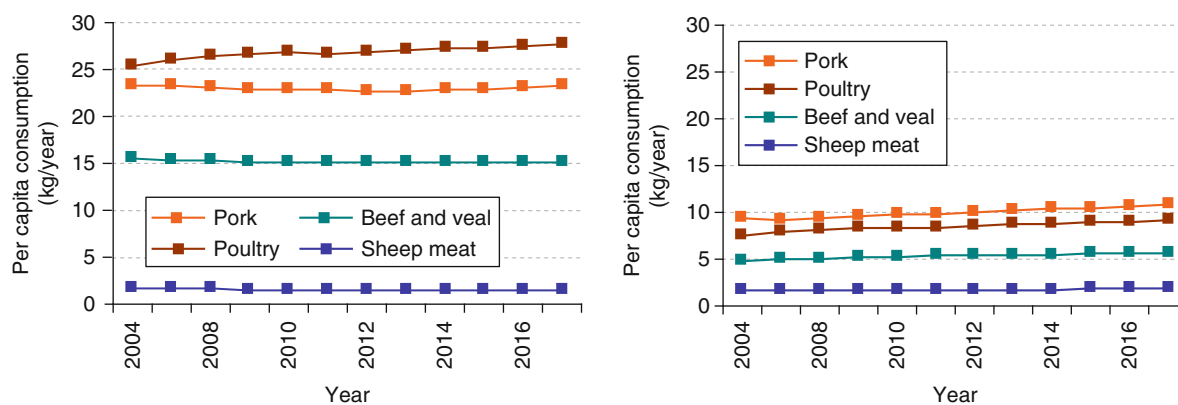
Per capita consumption of pork as well as of beef and veal is forecast to remain largely stable up to 2017 in the OECD countries, at respectively ~ 23 and ~ 15 kg/person/year (Fig. 13). The per capita consumption of poultry meat is expected to increase by 9% from 25.4 to 27.8 kg/person/year. In contrast, the consumption of sheep meat is predicted to decline by 11% from 1.8 to 1.6 kg/person/year. The ranking of the meat from the various species is consistent over years, the sequence being poultry, pork, beef and veal, and finally sheep meat. The per capita consumption of all meat types, with the exception of sheep meat, is forecast to be lower in non-OECD countries (Fig. 13). Per capita consumption of meat from all the different species is predicted to increase over time in the latter grouping. In sequence of the importance of the different types of meat, per capita consumption is expected to rise by 15% for pork (from 9.5 to 10.9 kg/person/year), by 22% for poultry (from 7.6 to 9.3 kg/person/year), by 18% for beef and veal (from 4.9 to 5.8 kg/person/year), and by 5% for sheep meat (from 1.9 to 2.0 kg/person/year).

It is evident from Fig. 13 that the wealthier OECD countries are able to sustain high levels of protein intake from livestock. With the exception of sheep meat, developing countries are lagging behind, suggesting that there is almost unlimited scope for the improvement of livestock productivity for meat

production in these regions. When the relatively small contribution of sheep meat in both regions is considered, it is tempting to discard this industry as an important contributor to food security. However, it is recognized that the sheep industry is able to thrive under marginal conditions where other livestock species find it difficult to adapt. Because of this, expansion in numbers (and thus product quantity) is not always easy to achieve. It is thus important to recognize the importance of this species to local food security, and also to the sustainable utilization of resources in marginal areas [8].

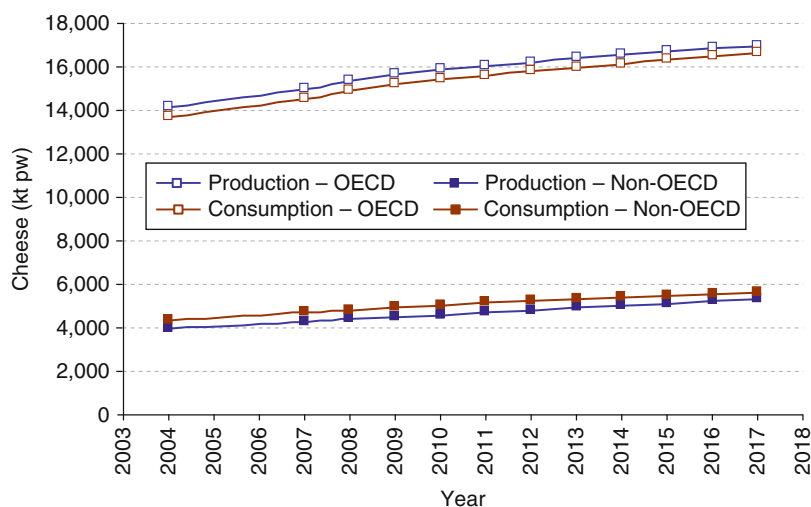
Dairy Products

The outlook is for both the OECD countries and non-OECD countries to increase their production and consumption of cheese in the immediate future (Fig. 14). Production is expected to increase from respectively $\sim 14,200$ and $\sim 4,000$ kt product weight (pw) in 2004 to respectively $\sim 17,000$ and $\sim 5,300$ kt pw in 2017. When expressed relative to 2004 production, these changes amount to respectively 20% and 35%. Corresponding increases in consumption amount to respectively 21% and 31%, from $\sim 13,700$ kt pw in OECD countries and $\sim 4,300$ kt pw in non-OECD countries to respectively $\sim 16,600$ and $\sim 5,700$ kt pw. As for other commodities, the surplus in OECD countries is forecast to be able to assist in alleviating the deficit in non-OECD countries.



Breeding in Developing Countries and Tropics. Figure 13

Per capita consumption of meat from the various species in the OECD countries (*left*) and in the non-OECD countries (*right*) for the period from 2004 to 2017 (Source: OECD-FAO [11])



Breeding in Developing Countries and Tropics. Figure 14

Cheese production and consumption in kiloton product weight (pw) in OECD and non-OECD countries (Source: OECD-FAO [11])

World production of goat cheese increased by 28% from 343 kt in 1985 to 438 kt in 2005 [15]. Regional production in the developing world more than tripled from 35 kt in 1985 to 122 kt in 2005, stayed constant at ~4 kt in South America, and declined by 13% from 114 kt in 1985 to 99 kt in 2005. In the developed world, European goat cheese production rose by 36% from 132 kt in 1985 to 180 kt in 2005, while production in northern and central America halved from 34 kt in 1985 to 18 kt in 2005. According to Dubeuf and Boyazoglu [15], selection of goats is limited to milk goats in developed countries. There thus seems ample scope to improve performance at all levels of the dairy goat industry in developing countries.

When butter is considered, it is evident that production and consumption are predicted to remain constant at respectively between 3,600 to 3,700 kt pw and 3,100 to 3,200 kt pw in OECD countries (Fig. 15). In the case of the non-OECD countries, production of butter is expected to increase by 68% from ~4,700 kt pw in 2004 to ~7,800 kt pw in 2017. Consumption is forecast to increase by 61% from ~5,100 to ~8,300 kt pw over the same period.

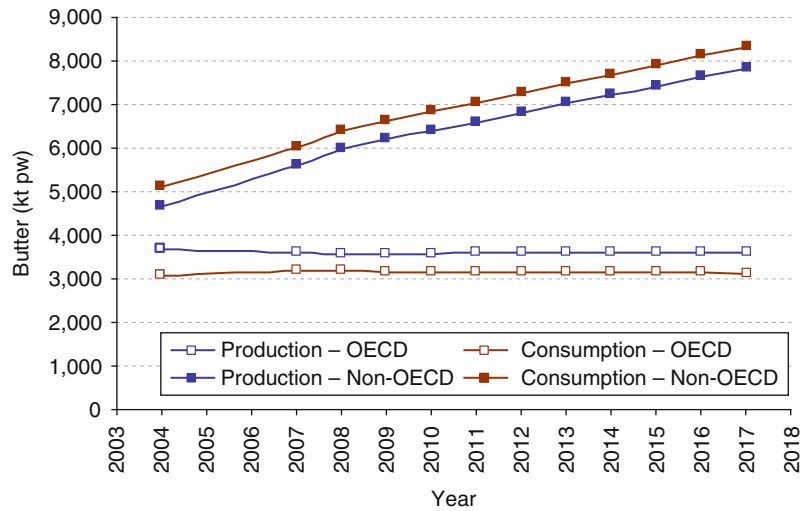
Milk powder production (the sum of skim milk powder production and whole milk powder

production) is projected to increase by 58%, from ~2,560 kt pw in 2004 to 4,060 kt pw in 2017, in non-OECD countries (Fig. 16). Consumption of milk powder is forecast to increase by 46%, from 4,140 to 6,030 kt pw over the same period. Both milk production and milk consumption remained fairly constant in OECD countries over the same period. The deficit between milk powder production and milk powder consumption in non-OECD countries is quite marked in this case. Fortunately the forecasted surplus of milk powder produced in the OECD countries will go a long way to alleviate this deficit in the non-OECD countries, as have been found for most of the other commodities.

It is evident that the production of butter and milk powder is substantially lower in OECD countries, compared to their non-OECD counterparts. In contrast, cheese production is much higher in OECD countries. This trend is understandable if it is considered that cheese is a prestigious, high-value product.

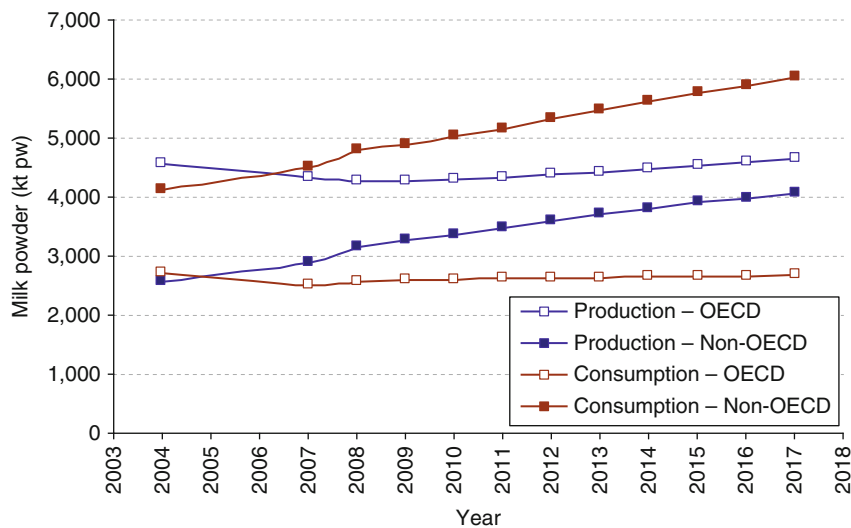
Challenges

It needs to be considered that livestock production in developing regions is faced with a number of challenges



Breeding in Developing Countries and Tropics. Figure 15

Butter production and consumption in kiloton product weight (pw) in OECD and non-OECD countries (Source: OECD-FAO [11])



Breeding in Developing Countries and Tropics. Figure 16

Milk powder production and consumption in kiloton product weight (pw) in OECD and non-OECD countries (Source: OECD-FAO [11])

to ensure sustainability [16, 17]. These challenges need to be overcome to ensure sustainable breeding programs. A broad subdivision can be considered as

challenges imposed by the environment (or external challenges) and those related to infrastructure and capacity (indicated as internal challenges).

External Challenges

Production under Various Systems It should be considered that the natural and/or cultivated plant resources form the basis for all types of livestock production. The more industrialized livestock sector relies on feedstuffs (concentrates, and roughages for dairy cows) that are in many cases imported from elsewhere for the sustenance of farmed animals. In contrast, natural and cultivated pastures are particularly important for the grazing ruminants that are able to convert low-quality roughage to nutritious protein for human consumption. Owing to a lack of control over pasture conditions in farming systems reliant on natural precipitation, periods of nutrient undersupply may occur. Persistent droughts may occur from time to time, adding to the challenges faced by tropical livestock [18]. Moreover, tropical pastures are known to have a high lignin content, particularly at the end of the growing season [19].

These afore-mentioned factors may act as constraints to efficient livestock production in developing and tropical regions. Low-potential extensive natural rangeland sustains a large portion of the well-developed sheep sector in South Africa [8]. Seasonal and unprecedented longer-term droughts are the rule rather than the exception. According to Mirkena et al. [19], adaptation of farm animals to such periods of feed scarcity can be achieved in a number of ways. Animals may develop a reduced metabolic requirement, or an ability to slow down metabolism. Digestive efficiency could be improved, while an improved utilization of low-quality roughage could be enabled. An alternative strategy could be to deposit adipose body reserves to act as a safeguard against periods of inadequate nutrient supply. As pertaining to a reduction in metabolic requirement, Silanikova [20] demonstrated that desert Bedouin goats have lower energy requirements than suggested by their body size, while they are also able to utilize low-quality roughage with a high fiber content. The latter type of goat also tolerated intake levels of ~50% below ad lib intake, compared to ~20% in Saanen goats. Localized fat reserves are found in a number of species adapted to harsh environments. Tail fat reserves of Horro and Mentz lambs were proportionally more reduced in comparison to

other fat depots during periods of food scarcity and resultant loss of body condition [21].

On the other hand, Fig. 13 clearly indicates that an increasingly large portion of per capita meat consumption is expected to be produced by poultry and pigs under more intensive production systems, also referred to as industrial systems [22]. This development leads to some challenges in itself. The intensification of animals on smaller areas is feared to lead to unprecedented spinoffs, like an increase in the transmission of diseases between animals and mankind [23]. This topic is dealt with in the next section, with a number of appropriate examples. However, it is important to note that some doubts exist about the governance of some countries in the developing world to adequately deal with this potential threat [23]. According to Gummow [23], this problem is compounded by a poor immune status in many countries because of diseases like HIV/AIDS. Additionally, child nutrition was found to be inadequate in many developing countries, leading to complications like stunting and retarded growth [6], as can also be inferred from Fig. 8.

Disease It is important to recognize that disease plays an important role in livestock production throughout the world, both in developing and developed regions. There is evidence that local, indigenous cattle developed tolerance to tsetse and trypanosomiasis challenge in parts of Africa infested by the tsetse fly [19]. A study by Van der Waaij [24] suggested that several quantitative trait loci (QTL) have a role to play in the tolerance of trypanosomiasis of cattle in the African tropics. Animals imported to these regions are not likely to survive, unless a high level of husbandry and the usage of appropriate chemical treatments are applied. Infestation of farm animals with ticks in developing countries often results in death owing to tick-borne diseases [25]. Local breeds of cattle, sheep, and goats are often tolerant to the challenge provided by such diseases [19]. In this respect, it has been shown that local Small East African goats were less likely to be affected by ticks and abscesses caused by ticks than imported Toggenburg goats in Tanzania [26]. Consistent differences in favor of the local Small East African goats were found for all three species of ticks that were considered in the study.

Analyses conducted on the national database of the Bonsmara breed in the South African National Beef Recording and Improvement Scheme indicated useful genetic variation in tick numbers, particularly when the data were structured to involve environments with a higher level of tick infestation [27]. Genetic variation on the underlying liability scale was also reported for the ability of Merino sheep to resist breech strike by the sheep blowfly, *Lucilia cuprina* [28–30]. The significant genetic variation was supported by distinct line differences between Merino lines divergently selected for their ability to rear multiple offspring [31]. The challenge of animals with breech strike is controversial from an ethical viewpoint, while the transient nature of breech strike makes an adequate natural challenge under all conditions infeasible. Alternatively, it has been suggested that indicator traits should receive some attention. Traits that are considered include breech fold score, dag score, breech cover score, and crutch cover score. A number of studies suggested that all these indicator traits show significant genetic variation [28, 29, 32, 33]. In general, the indicator traits were not unfavorably related to wool and fleece traits. There is also some evidence that dag score [28, 29], breech cover score [29], and breech fold score [30] are genetically related to breech strike. Earlier work also suggested a genetic basis for body strike in sheep, as reviewed by Morris [34]. Selection for combined resistance to body strike and fleece-rot also resulted in genetic gains that accorded with expectations [35]. Infestation with the sheep body louse, *Bovicola ovis*, was accordingly reported to be heritable in a New Zealand study [36]. However, lice infestation was not conclusively associated with susceptibility to gastrointestinal nematodes.

Most species of farmed livestock are also affected by internal parasites. In this respect, marked breed differences in resistance to *Haemonchus contortus* were reported between the indigenous Kenyan Red Maasai sheep compared to the Dorper breed, an import from South Africa. Indigenous Red Maasai sheep had lower parasite burdens (as reflected by fecal worm egg counts), higher packed cell volumes as well as an improved lamb survival compared to Dorpers [37]. A later study reported small breed differences in a more arid environment with an inherently lower

parasite challenge [38]. The relative advantage of the Red Maasai became evident in an environment conducive to helminth infestation, as reflected by a threefold advantage in levels of production on Red Maasai sheep compared to Dorpers [38]. Nimbkar et al. [39] reported corresponding differences in crosses of the Garole breed with the Banmur and Deccani breeds in India. These breed differences are supported by ample evidence of genetic variation in fecal worm egg counts as a measure of resistance to gastrointestinal roundworms in sheep [40, 41], as well as realized genetic progress [34, 41, 42]. Selection for lower fecal worm egg counts resulted in lower outputs of larvae on the pasture by reproducing ewes [43] and concomitant economic gains [44].

Genetic parameters and progress in other diseases of sheep were reviewed by Morris [34]. Apart from four mycotoxic diseases, the review also considered bacterial diseases like mastitis, footrot, and pneumonia. All diseases have shown moderate genetic variation, and realized genetic gains were reported for facial eczema and ryegrass staggers. Mastitis and footrot also formed part of the review by Bishop [45], indicating how the epidemiology of transmittable diseases affects options to utilize genetic variation in disease resistance in a number of species. In dairy cattle, improved modeling and revised trait definitions are being investigated for usage in the genetic improvement of resistance to mastitis on a national scale, as based on readily available somatic cell count data [46, 47]. Similar studies are underway as pertaining to bovine Johne's disease [48] and bovine tuberculosis [49].

Additionally, cognizance should be taken of new diseases of a noninfectious nature. Gummow [23] pointed out that increased industrialization and pollution also impacted on livestock farming, and listed chronic copper and vanadium overdose as an important source of livestock deaths in the Mpumalanga province of South Africa. Other examples of noninfectious conditions listed in the latter review were the impact of environmental contaminants on the life expectancy of humans in Russia as well as air pollution in the United States. These conditions need to be understood better, while pollution needs to be brought down to manageable levels [23].

The previous discussion dealt with the importance of disease, as well as heritable resistance to known pathogens. The complexity of selection for resistance to known pathogens, as reviewed by Bishop [45], is also recognized. The relevance of the above-mentioned to the eventual outcome of the chapter will become clear in the section on future directions.

It is important to note that intensification in the more industrialized livestock species (poultry, pigs, and dairy cows) are likely to be conducive to an increased risk of infection by some diseases [23]. Owing to close contact with mankind, the transmission of some animal diseases to humans (also referred to as zoonoses) places a further dimension on the importance of livestock disease. A number of recent and historic epidemics, resulting in loss of life among animals and humans alike, have been listed by Gummow [23]. The transmission of animal diseases to humans falls beyond the scope of this review, and will not be dealt with in detail. However, it is necessary to refer briefly to recent occurrences of Bovine Spongiform Encephalopathy (better known as BSE), foot and mouth disease, and Avian Influenza to get an indication of the impact of such diseases on mankind. Avian Influenza in particular has led to recent scares, associated with a loss of approximately 200 human lives [22]. An outbreak of Rift Valley Fever during the summer and autumn of 2010 similarly resulted in substantial livestock losses [50], as well as at least 17 human fatalities in South Africa during the past year [51]. This has resulted in the suspension of raw wool exports worth an estimated 1 billion South African Rand (ZAR) to the Chinese market on August 16, 2010 [52]. The impacts of such events on livestock, humans, and the economy should be clear from the foregoing.

Heat Stress and Water Requirements The climate can influence animal production in many ways. The impact of low and unreliable rainfall patterns already received attention previously. One of the other main stressors of livestock in the developing world, and particularly in the tropics, is heat [19]. Heat stress is reflected in increases in a number of physiological responses that result in impaired production and reproduction [53]. Heat stress is aggravated by an increased humidity [19]. According to Marai et al.

[53], the following temperature humidity index (THI) can be an indication of the amount of heat stress experienced by animals:

$$\text{THI} = \text{db}^{\circ}\text{C} = [(0.31 - 0.31 \text{ RH})\text{db}^{\circ}\text{C} - 14.4]$$

With $\text{db}^{\circ}\text{C}$ = the dry bulb temperature in $^{\circ}\text{C}$

RH = the relative humidity (RH%/100w)

Values below 22.2 suggest an absence of heat stress, a value from 22.2 to <23.3 is indicative to moderate heat stress, a value from 23.3 to <25.6 suggests severe heat stress and a value exceeding 25.6 reflects extreme heat stress. It is suggested that adapted animals are able to increase their sweating rate under adverse conditions in terms of heat stress, while they are able to control heart rate and rectal temperature better than their poorly adapted contemporaries.

A Brazilian study compared a number of physiological responses of five naturalized Brazilian cattle breeds (Curraleiro, Crioulo Lageano, Pantaneiro, Junqueira, and Mocho Nacional – the former four breeds from a *Bos taurus ibericus* origin and the latter from a *B taurus ibericus* x *B taurus aquitanicus* origin), as well as the commercially available Holstein (*B taurus taurus*) and Nellore (*B taurus indicus*) breeds [54]. Of the latter two breeds, it was thought that the Holstein would be poorly adapted to heat stress, while the Nellore was thought to be well adapted. Physiological traits measured on the animals are reported in Table 8.

The temperatures were not extreme during the duration of the study. Maxima ranged from just above 20°C to just below 30°C , while minima ranged from $\sim 12^{\circ}\text{C}$ to $\sim 22^{\circ}\text{C}$. Humidity ranged from $\sim 50\%$ to 90% in the mornings and from $\sim 25\%$ to $\sim 58\%$ in the afternoons. Although all physiological traits in Table 8 were within normal ranges for cattle, it is notable that Nellore cattle consistently had a lower rectal temperature, respiration rate, sweating rate, serum cortisol concentration, and packed cell volume compared to their Holstein contemporaries. Rectal temperature of Holstein cattle differed by 1.4°C from the morning to the afternoon, whereas all the other breeds differed by less than 1.1°C . The respiration rate of Holstein cattle also differed by 5.7 movements/min from the morning to the afternoon, compared to 0.4 movements/min in the Junqueira breed. Based on the packed cell volume and total plasma protein

Breeding in Developing Countries and Tropics. Table 8 Means for physiological traits of five naturalized Brazilian cattle breeds, as well as the Holstein and Nellore breeds

Breed	Physiological trait						
	RT	RR	HR	SR	Cort	PCV	TPP
Crioulo Lageano	38.7	33.8	64.4	242	14.8	32.1	7.34
Curraleiro	38.8	31.0	70.7	251	11.6	34.3	7.34
Junqueira	38.7	26.4	69.9	234	14.7	32.7	7.40
Mocho Nacional	38.8	38.8	70.6	259	13.6	35.0	7.23
Pantaneiro	38.8	33.3	69.9	252	15.9	36.8	7.50
Holstein	39.0	32.7	62.6	258	13.8	37.7	7.34
Nellore	38.6	27.7	68.9	225	12.0	33.1	6.99

RT Rectal Temperature ($^{\circ}\text{C}$), RR Respiration rate (movements/min), HR Heart rate (movements/min), SR Sweating rate (g/m/h), Cort Serum cortisol concentration (ng/mL), PCV Packed cell volume, TPP Total plasma protein

Source: Adapted from McManus et al. [54].

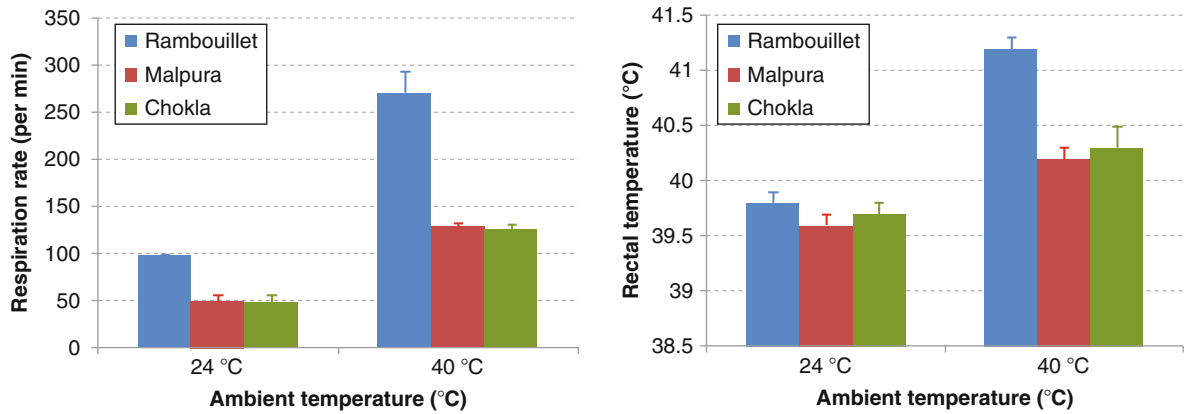
concentration, it was suggested that Holstein cattle were more dehydrated than the other breeds, and the Nellore breed in particular. The clear breed differences in Table 8 clearly suggest that the Holstein would be less adapted to heat than the Nellore breed, as anticipated. Of the naturalized breeds, the Junqueira seemed to be best adapted. In contrast, adaptation of the Mocho Nacional breed appeared to be the worst among the naturalized breeds.

The impact of heat stress on sheep was reviewed by Marai et al. [53]. Lambs borne by heat-stressed ewes had lower birth weight than those of ewes not subject to heat stress. The impact seems to be brought about by a reduction in embryo cell number and placental size. Heat stress also depressed lamb growth, with solar radiation together with heat stress aggravating the situation. Exposure of sheep to heat stress conditions leads to impaired feed intake levels, as well as increases in respiration rate, body temperature, and water intake. The digestion of forage is also impaired by the exposure of sheep to heat stress conditions [53].

The physiological response of a temperate sheep breed (Rambouillet) was compared to those of two Indian breeds (Malpura and Chokla) at ambient temperatures of 24°C and 40°C in a study by Singh et al. [55]. The better adaptation of the Indian breeds to the ambient temperature of 40°C is evident in Fig. 17, as reflected by reduced respiration rates and rectal temperatures.

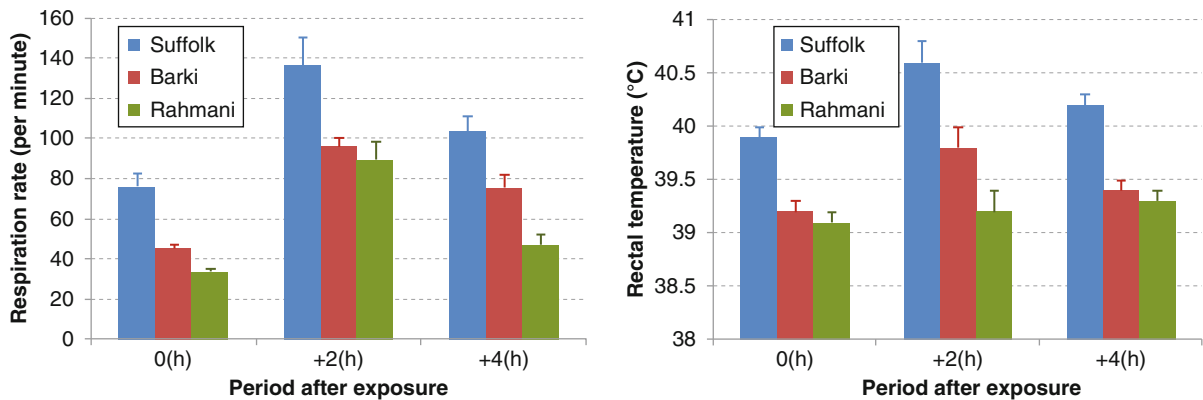
Very similar results were reported for Suffolk sheep, as representative of a temperate breed relative to local Egyptian breeds (the Barki and Rahmani) in the study of El-Sheikh et al. [56]. In this study, respiration rate and rectal temperature were studied at exposure to elevated temperatures (0 h), and after 2 and 4 h of exposure to high temperatures (respectively +2 h and +4 h). The better adaptation of the two local breeds compared to the Suffolk is evident from Fig. 18.

The better adaptation of local breeds to conditions of excessive heat is evident from the foregoing. It could therefore be expected that animals from temperate breeds could find it difficult to adapt and thrive under such conditions. Menjo et al. [16] reported that 25% of Holstein-Friesian heifers born from artificial insemination in Kenya were lost to involuntary culling prior to their first calving. It is notable that the survival of heifers bred from semen of Kenyan, South African, and Israeli bulls had an improved survival relative to those bulls originating from Australia, New Zealand, the United States, and Canada. Conditions in terms of ambient temperature in the dairy producing areas of the latter countries are arguably cooler than those experienced in Kenya, while harsher conditions are expected in South Africa and Israel. Unfortunately, the relative milk yields of the heifers that originated from semen from the respective regions were not reported and could, thus, not be considered. Boonkum et al. [57] accordingly reported that days open were



Breeding in Developing Countries and Tropics. Figure 17

Means for respiration rate (*left*) and rectal temperature (*right*) of animals from the Rambouillet, Malpura, and Chokla sheep breeds at ambient temperatures of 24°C and 40°C (Adapted from Singh et al. [55])



Breeding in Developing Countries and Tropics. Figure 18

Means for respiration rate (*left*) and rectal temperature (*right*) of animals from the Suffolk, Barki, and Rahmani sheep breeds after 2 and 4 h of exposure to elevated temperatures (adapted from El-Sheik et al. [56])

increased with an increased proportion of Holstein genes in Thai Holstein and Holstein cross cows. The heritability of days open was slightly higher for summer calvings compared to late rainy season calvings. Susceptibility to heat stress increased with increasing parities, possibly leading to the observed high erosion rates of cows from first to third parity [58]. Whereas genetic trends for milk yield was favorable from first to third parity, second and third lactation cows became more susceptible to heat stress with time. These effects are expected to be aggravated with global warming. It is reassuring that statistical methods are sufficiently

robust to rank animals for heat tolerance for selection purposes. Genomic selection is expected to improve the accuracy of evaluating young animals for selection purposes.

Many developing countries are in water-scarce areas of the world. It is therefore important to consider adaptation of livestock to water scarcity. Mirkena et al. [19] noted that breeds originating from arid countries can withstand water deprivation for longer periods than their counterparts from temperate countries. Camels are extremely well adapted in this sense, being able to withstand water deprivation for 17 days

on dry feed [59] and for 30–60 days on green feed [60]. There are also donkey, goat, sheep, and some cattle breeds that are able to go without water for several days [61]. Black Bedouin and Barmer goats in the Middle East may go for 4 days without water [20]. Adapted breeds minimize water losses in urine and feces and are able to produce milk despite low water intakes. Because of the increasing strategic importance of water, production practices for the future should adopt water conservation practices [62].

The adaptation of local tropical breeds to extreme conditions was discussed in this section. The importance of this adaptation to breeding in the developing world will become clear in subsequent sections.

Internal Challenges

Infrastructure and Capacity Regions in the developing world were shown to lack infrastructure and capacity for the management of animal genetic resources (Table 9).

Between 71% and 100% of African countries had limited or no capacity in the seven categories that were considered. The situation in Asia was more variable. The central and southeastern parts had limited capacity, while conditions in the east and south were somewhat better. The capacity of the Southwest Pacific, Central America, and the Near and Middle East was also limited with 78–100% of the countries having

Breeding in Developing Countries and Tropics. Table 9 Assessment of regional capacities for the management of animal genetic resources for food production

Region	Physical infrastructure		Intellectual infrastructure		Policy development		
	Capacity	Participation	Research	Knowledge	Awareness	Laws	Implementation
Africa							
North and West Africa	92	96	87	87	87	96	96
East Africa	71	100	71	86	71	86	100
Southern Africa	82	82	100	100	91	91	100
Asia							
Central Asia	100	100	100	100	100	100	100
East Asia	50	50	75	25	50	50	50
South Asia	43	71	43	85	43	71	86
Southeast Asia	75	100	75	75	75	50	75
Southwest Pacific	91	91	91	91	91	91	91
Europe and the Caucasus	31	31	36	33	31	36	46
Latin America and the Caribbean							
Caribbean	33	67	33	33	33	67	67
Central America	78	78	78	78	78	78	78
South America	30	70	30	50	50	60	50
North America	0	0	0	0	0	50	0
Near and Middle East	86	100	85	86	86	100	100

Source: Adapted from Brockhaus [63].

The percentage of countries having no or limited capacities are listed with reference to physical infrastructure, intellectual infrastructure, and policy development. The balance of countries would have medium to high scores in these respects.

limited or no capacity in the categories that were considered. The capacity of the South American and the Caribbean regions were intermediate in this respect, with between 30% and 70% of the countries having no or limited capacity in one or more of the categories under consideration. In contrast, the developed countries in Europe and the Caucasus and North America consistently had moderate to good capacities in 50% or more of the categories under consideration. The situation in North America in particular is good, with 100% of the countries having medium to good capacity in all categories except for the existence of laws and political programs.

The scenario set out in Table 9 led to an assessment by Brockhaus [63] that the strategic action as pertaining to genetic resource management has a sound basis in North America, Europe and the Caucasus, and, to a lesser extent, in Latin America and the Caribbean. Legislation in the former regions is well underway to regulate animal genetic resources. Weaknesses in the developing world are not only present at a strategic level but also at the basic operational and organizational levels. It thus seems that efforts to improve the vast and diversified livestock genetic resource of the developing world are constrained by several factors [64]. On the positive side, a growing level of awareness is present in the other regions [63]. This provides an opportunity to identify countries and stakeholders that may act as catalysts of development in other countries

of the regions lagging behind. Local, regional, and international stakeholders that could play a role in this respect were listed by the latter literature source.

Structured Programs From Table 9 it is evident that the capacities to ensure structured livestock improvement may be lacking in most countries of the developing world. The emphasis placed on structured breeding programs for the livestock species of interest in the different regions must thus be considered next. The species most likely to be involved in structured breeding programs worldwide is cattle, followed by sheep, goats, pigs, and chickens (Table 10). Breeding of both dairy and beef cattle is also considered as a priority by the largest number of countries. Regions with below 50% countries involved in structured cattle breeding programs are Africa (31%), the Near and Middle East (14%), the Caribbean and Central America (17%), and the Southwest Pacific (13%). Structured sheep and goat breeding is practiced less widely, with the only regions where programs are in place in 50% or more of the countries being Europe and the Caucasus, as well as North America in the developed world, and only the Near and Middle East in the developing World. The situation for structured goat breeding is much the same except for fewer than 50% of the countries in the Near and Middle East having programs in place. It is of interest that sheep and goat breeding was only considered as a priority in four African countries [65]. This

Breeding in Developing Countries and Tropics. Table 10 Percentages of countries reporting structured livestock breeding programs per species in the regions of interest

Region	Chickens	Cattle	Sheep	Goats	Pigs
Africa	2	31	10	10	6
Asia	16	58	30	32	19
Near and Middle East	14	14	57	43	0
Europe and the Caucasus	23	74	59	54	62
Caribbean and Central America	8	17	17	8	8
South America	20	60	10	10	10
North America	50	100	50	50	100
Southwest Pacific	9	13	40	0	18
<i>World</i>	14	47	33	27	27

Source: Adapted from Thieme [65].

situation is perplexing, as Africa is the continent with the third highest sheep population and the second largest goat population worldwide (Table 4). Structured pig breeding is basically only being practiced in the developed world countries in the Europe and Caucasus and North American regions. The North American region is basically the only region where structured poultry breeding is practiced by 50% of the countries. The lack of activity in pig and poultry breeding in most regions can be related to breeding in these species being mostly entrusted to international breeding companies with worldwide marketing capabilities.

Tools and Strategies in Livestock Breeding Breeding in pigs and poultry is mostly centralized and practiced at low levels in the developing world. These species will thus not be covered in this section.

There is clearly a lack of activities associated with animal genetic resource management of cattle in Africa, Asia, as well as in the Near and Middle East, when compared to the situation in the developed countries of Europe and the Caucasus (Table 11). Countries in Latin America and the Caribbean are well situated as far as identification, performance recording, and artificial insemination of cattle are concerned. However,

Breeding in Developing Countries and Tropics. Table 11 The percentage of cattle and sheep breeds applying tools integral to livestock breeding during the process of breed improvement

Region	Africa	Asia	Near and Middle East	Europe and the Caucasus	Latin America and the Caribbean
Cattle breeds with:					
Breeding goal	18	28	14	44	4
Strategy implemented	13	24	9	44	1
Individual identification	11	12	9	44	58
Performance recording	12	16	9	42	45
Artificial insemination	23	12	23	38	69
Genetic evaluation	9	12	5	38	24
Sheep breeds with:					
Breeding goal	14	33	16	52	5
Strategy implemented	9	33	8	50	5
Individual identification	9	2	8	45	31
Performance recording	8	2	8	45	14
Artificial insemination	2	17	0	12	35
Genetic evaluation	5	18	0	21	37
Goat breeds with:					
Breeding goal	21	12	13	28	12
Strategy implemented	15	12	13	25	12
Individual identification	18	3	6	33	27
Performance recording	21	3	13	30	22
Artificial insemination	5	3	0	5	31
Genetic evaluation	16	3	0	10	27

Source: Adapted from Thieme [65].

most cattle breeds in this region lack a breeding goal and a breeding strategy.

Genetic resource management of sheep breeds in Africa, Asia, and the Near and Middle East is clearly hampered by a lack of identification of individuals and performance recording (Table 10). A third of Asian sheep breeds have a breeding goal and selection strategy in place. This is in contrast with Latin America and the Caribbean, where these aspects of animal resource management are lacking. However, the latter region performs better for the recording of individual animals, artificial insemination, and genetic evaluation. Artificial insemination and genetic evaluation of sheep are in fact better placed in Latin America and the Caribbean than in the developed regions of Europe and the Caucasus. About half the sheep breeds in these developed regions have breeding goals, selection strategies, as well as individual identification and recording in place.

The situation regarding goat breeds are quite similar to that in sheep, but with generally higher levels of uptake of genetic strategies and tools in African goat breeds (Table 11). In contrast, goat genetic resource management in the developed countries of Europe and the Caucasus are generally on lower levels compared to sheep. The lower uptake of artificial insemination in small ruminants compared to bovines is notable. This trend is probably related to the lack of a reliable trans-cervical insemination protocol in the small ruminant species.

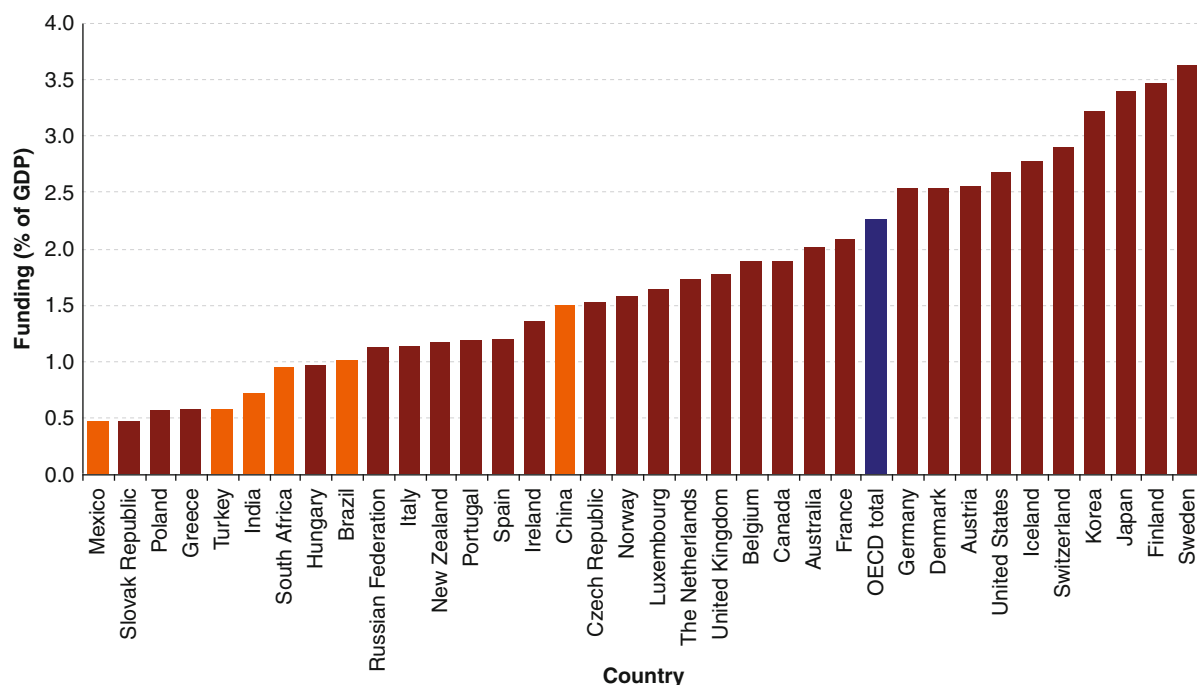
The most important stakeholder in determining breeding goal definition was identified as research organizations in all regions [65]. The identification of individual animals also appears to be mostly driven by research institutions. The exception to this rule was in Europe and the Caucasus, where it was mostly driven by breeders and governments. Recording of animal performance is mostly driven by research organizations in Africa, by governments and breeders in Asia, by nongovernmental organizations in the Near and Middle East, and by breeders in Europe and the Caucasus. Genetic evaluation is seen as the responsibility of research organizations in all regions.

Crossbreeding programs to complement purebreeding efforts were reported in all species and all regions [65]. Crossbreeding seems to be more prevalent in cattle and goats compared to sheep.

Research Expenditure The importance of research organizations in the evaluation of animal genetic resources has been highlighted in the previous section. It is therefore relevant to consider the state of research funding in countries of the developing world and in the developed world (Fig. 19). The developing countries (orange bars) with the highest research expenditure in terms of gross domestic product (GDP) is China at 1.49%. Other developing countries are Brazil (1.02%), South Africa (0.95%), India (0.71%), Turkey (0.58%), and Mexico (0.46%). Research expenditure of countries in the developed world (dark red bars) ranged from 0.47% of the GDP for the Slovak Republic to 3.63% of the GDP for Sweden. The average research expenditure for OECD countries (blue bar) amounted to 2.26% of GDP.

Figure 19 provides information on research in general. Agricultural research is often not the area of scientific development attracting the highest level of funding. Information on South Africa as an example of a fairly prosperous developing economy is provided to demonstrate this point. Of a total research budget of ~ZAR 16.5 billion in 2006/2007, funding of research and development in Agricultural Sciences amounted to 6.9% [67]. This figure was substantially lower than those for Engineering Sciences (21%), Medical and Health Sciences (15%), Information, Computer and Communication Sciences (14%), Applied Sciences and Technologies (11%) and Social Sciences (9.4%). Of the ~ZAR 1.14 billion invested in Agricultural Sciences, only ~ZAR 0.34 billion are dedicated to research on animal production and animal primary products. This amounts to approximately 2% of the overall research and development budget.

During 2006/2007, the contribution of different sectors of the South African economy to agricultural research and development (the gross value of research and development is provided in Table 12) amounted 3.0% for the business sector, 16.7% for the governmental sector, 4.6% for the higher education sector, 8.1% for nonprofit organizations and 19.0% for science councils. Compared to 2004/2005 figures, research and development expenditure increased by 37% in the business sector, by 98% in the government sector, by 30% in the higher education sector, and by 38% for science councils. No consistent increase was evident in the research and development expenditure of nonprofit



Breeding in Developing Countries and Tropics. Figure 19

Research funding expressed as a percentage of the gross domestic product (GDP) for a number of countries. Developed countries are depicted in dark red, developing countries in orange, while the blue bar depicts the average of the OECD countries (Source: OECD [66]).

organizations. The share of agricultural research remained relatively stable in the business and higher education sectors as well as in the science councils. In contrast, the percentage of governmental research and development funds devoted to agricultural research halved over the same period (Table 12). The gross value of governmental research on animal production and animal primary products increased slightly from ZAR 0.058 billion during 2004/2005 to ZAR 0.067 billion during 2006/2007. However, the percentage of the total budget devoted to these study fields declined from 11.2% to 7.0% over the same period [67]. A modest increase in the share of agricultural research was recorded for nonprofit organizations. The contribution of this sector is probably not that important if it is considered that research by nonprofit organizations attract a relatively small fraction of the overall research funding (according to Table 12 only 1.2% of the overall research and development budget).

Given the importance of governments and other stakeholders in research in decision-making pertaining

to livestock breeding [65], the reduction in the percentage of governmental funds allocated to agricultural research and development is disconcerting. If it is considered that South Africa has been identified as an emerging economy along with Brazil, Chile, China, India, Russia, and Ukraine [68], it is evident that the situation may be worse in other countries in the developing world. There thus seem to be a need for a concerted effort to consolidate funding for research pertaining to livestock genetic resources in the countries of the developing world.

Intellectual Capacity The previous heading was concerned with the funding of research in the developing world. Apart from the monetary needs, the functioning of all research organizations also depends on the number and quality of the researchers employed. The number of researchers per 1,000 members of the population in a number of developed and developing countries thus needs to be considered. It is clear that developing countries (orange bars) have substantially

Breeding in Developing Countries and Tropics.

Table 12 Changes in South African research and development expenditure for Agricultural Sciences in the recent past, expressed relative to the total expenditure on research and development in the business, governmental, and higher education sectors, as well as nonprofit organizations and science councils

Sector and expenditure	Year		
	2004/ 2005	2005/ 2006	2006/ 2007
Business			
Total R&D (ZAR billion)	6.766	8.244	9.243
Agriculture (%)	2.8	3.1	3.0
Governmental			
Total R&D (ZAR billion)	0.515	0.844	1.021
Agriculture (%)	33.9	18.5	16.7
Higher education			
Total R&D (ZAR billion)	2.534	2.732	3.299
Agriculture (%)	3.8	5.2	4.6
Nonprofit organizations			
Total R&D (ZAR billion)	0.198	0.227	0.212
Agriculture (%)	6.4	7.3	8.1
Science councils			
Total R&D (ZAR billion)	1.996	2.102	2.745
Agriculture (%)	19.7	18.4	19.0

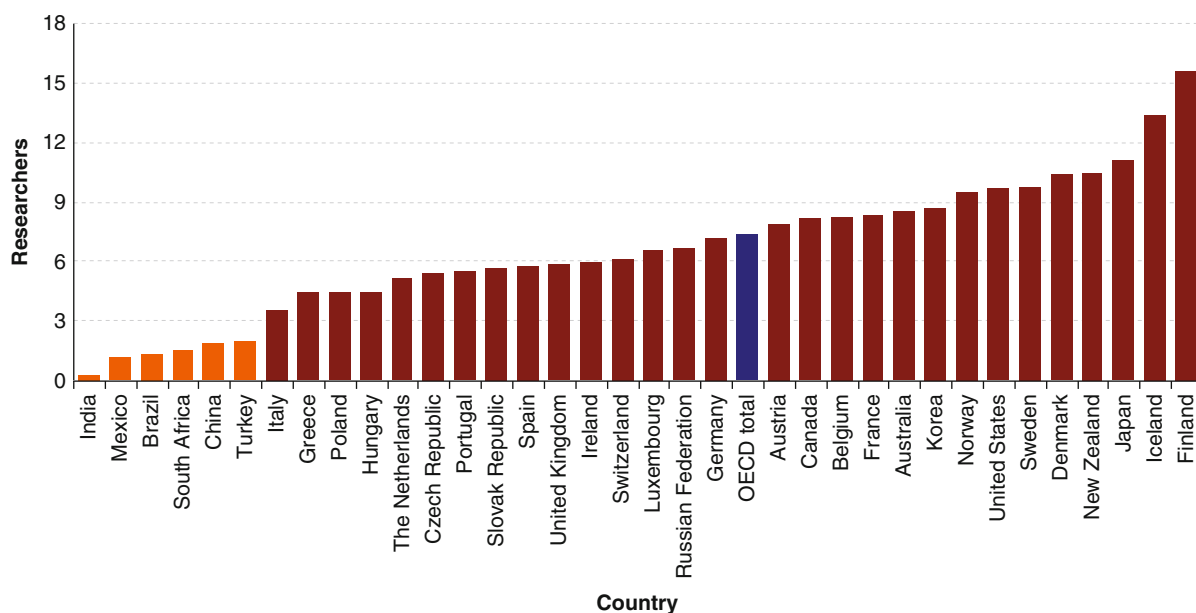
Source: Adapted from Anon [67].

fewer researchers in employment per 1,000 population members when compared to developed countries (Fig. 20). The numbers of researchers per 1,000 population members in developing countries ranged from 0.3 in India to 1.9 in Turkey. In contrast, between 3.6 (Italy) and 15.7 (Finland) researchers were employed per 1,000 population members in the developed world, giving an average of 7.3 researchers per 1,000 population members for OECD member countries. The number of researchers per 1,000 population

members in the developed world is thus substantially higher than in the developing world.

The discrepancy in the number of researchers per 1,000 population members is evident from Fig. 20. It is of interest to note the trend in the employment of researcher fulltime equivalents in a developing country like South Africa. Firstly, it is important to note that close to 50% of all the researcher fulltime equivalents in South Africa were employed by the business sector in 2006/2007 (Table 13). The higher education sector accounted for another 29%, science councils for 16%, the governmental sector for 6%, and nonprofit organizations for 1.6%. Overall, the number of researcher fulltime equivalents increased by 15% from 11,080 in 2004/2005 to 12,739 in 2006/2007 [67]. A similar increase was noted in the business sector, while the number of researcher fulltime equivalents in the governmental sector increased by a substantial 60%. The number of researcher fulltime equivalents in the higher education sector was fairly stable, while nonprofit organizations suffered a 13% decline in researcher fulltime equivalents. The number of researcher fulltime equivalents in science councils decreased by 15% from 2004/2005 to 2005/2006, but recovered to a level 28% higher than in 2004/2005 during 2006/2007. It is notable that researchers contributed about 50% to all research related personnel in the business sector (Table 13). Researchers formed a more commanding part of the personnel corps in the higher education sector (71–77%) and in nonprofit organizations (56–69%). In contrast, the support personnel appeared to have the lion's share of the personnel corps at the expense of researchers in the government sector (30–44%) and in science councils (31–40%). The latter similarity is not surprising, as the science councils are parastatal organizations receiving part of their budgets from the government coffers.

From the foregoing, it can be deduced that scientists in the developed world are often faced with particular challenges relative to their counterparts in the developed world. One of these should be a heavier workload, to make up for the deficit in manpower as reflected in Fig. 20. It is therefore not surprising that South African professionals were found to spend longer times at the office compared to their colleagues in the United States, United Kingdom, and Australia in a survey conducted between June 2010 and July 2010 [69].



Breeding in Developing Countries and Tropics. Figure 20

The number of researchers expressed per 1,000 population members for a number of countries. Developed countries are depicted in dark red, developing countries in orange, while the blue bar depicts the average of the OECD countries (Source: OECD [66]).

In 25% of the professionals interviewed, this situation was aggravated by inconsistent internet access. In view of South Africa's assessment as a developing economy [68], it is expected that the situation in many other developing countries could be worse.

It needs to be stated that the results provided in Fig. 19 and in Table 13 are for research in general and not for agricultural research in particular. Unfortunately, the information pertaining to researcher fulltime equivalents was not broken down to the level of research field as for the expenditure on research reported in Table 12. The increase in the number of researchers has to be viewed positively, noting that research and development in a country is needed for sustained growth and global competitiveness [67]. On the other hand, it has already been shown that the emerging economy of South Africa invested only 6.9% of the total research and development budget in agricultural research (Table 12). As high-level researchers are often attracted to better funding opportunities, it is likely that the agricultural sector could find it difficult to recruit and retain the most promising

young scientists. Moreover, the increase in the number of researcher full time equivalents is unlikely to be met with immediate success, as its impact still needs to filter through with time.

Against this background, it is not surprising that animal resource management is suboptimal in most countries in the developing world, as depicted in Tables 9–11. Therefore it is important to consider ways to ensure that services with respect to animal resource management are delivered to producers in these regions, given the important contribution of livestock to food security and rural sustainability. In this process it is fitting to have a look at how the developing world contributes to the global science output.

The Contribution of Developing Countries to Global Science The recent 9th World Congress on Genetics Applied to Livestock Production (WCGALP) was held from August 1 to August 6, 2010, in Leipzig, Germany. WCGALP provides an opportunity to take stock of global research efforts involving livestock production every 4 years. The relative contribution that stemmed

Breeding in Developing Countries and Tropics. Table 13 Changes in the number of South African researchers (expressed in full-time equivalents – FTE) in the recent past, expressed relative to the total number of FTE active within research and development (R&D) in the business, governmental, and higher education sectors, as well as nonprofit organizations and science councils

Sector and researcher fulltime equivalents	Year		
	2004/2005	2005/2006	2006/2007
Business			
Researcher fulltime equivalents (n)	5,300	5,896	6,111
Percent of personnel involved in R&D	46.9	48.2	48.5
Governmental			
Researcher fulltime equivalents (n)	491	651	784
% of personnel involved in R&D	29.5	43.9	37.9
Higher education			
Researcher fulltime equivalents (n)	3,506	3,555	3,658
Percent of personnel involved in R&D	77.1	72.1	70.8
Nonprofit organizations			
Researcher fulltime equivalents (n)	234	198	203
Percent of personnel involved in R&D	64.5	69.2	55.9
Science councils			
Researcher fulltime equivalents (n)	1,549	1,323	1,983
Percent of personnel involved in R&D	31.0	32.2	40.0

Source: Adapted from Anon [67].

from scientists in the developing world can be assessed simultaneously. The country of origin of the first author of each abstract of oral contributions during concurrent sessions and of posters displayed during poster sessions was recorded and summarized in Table 14. None of the eight plenary lectures that were presented during the congress was by scientists or groups of scientists from the developing world. The contribution of the developing world to papers presented during concurrent sessions will be considered next. The contribution of scientists from the developing world ranged from 4% in the case of the topic “genetics of trait complexes” to 12.5% for the topics “genetic improvement programs” and “special topics” (Table 14). Cases where contributions from the developing world exceeded 10% of all contributions within subtopics will be noted subsequently. Within the topic of “species breeding,” the developing world

contributed most toward “small stock breeding” (33.3% of 21 papers), “poultry breeding” (20.0% of 20 papers), and “aquaculture” (18.8% of 16 papers). The contribution of scientist groups in the developing world to small stock breeding should probably be seen in context with the projected and current trends in sheep meat in Fig. 12. Pertaining to the topic “Genetics of trait complexes” one of nine papers on “behavior” (11.1%) was presented by scientists from the developing world. The developing world does not seem to be active on the topic “methods and tools” as no subtopic attracted 10% or more of the papers in this case. When the topic “genetic improvement programs” was considered, groups from the developing world contributed most papers to the subtopic “breeding objectives and economics of selection schemes” (40% of 10 papers), “management of genetic resources” (26.1% of 23 papers) and “selection for harsh environments

Breeding in Developing Countries and Tropics. Table 14 Contributions to the concurrent paper or poster sessions of the 2010 World Congress on Genetics Applied to Livestock Production per topic, with the contributions from developing countries as percentage

Topic	Papers ^a		Posters ^a		Total ^a	
	N	%	N	%	N	%
Species breeding	164	11.0	181	49.2	345	31.0
Genetics of trait complexes	101	4.0	79	27.8	180	14.4
Methods and tools	90	4.4	46	30.4	136	13.2
Genetic improvement programs	96	12.5	52	32.7	148	19.6
Special topics	24	12.5	2	0	26	11.5

^aNumber of contributions within categories (N) and percentage contributed by the developing world (%).

Source: Adapted from WCGALP [70].

(e.g., the tropics)” (11.1% of 9 papers). Given the location of most developing countries, it is somewhat surprising that the major contribution of the latter subtopic still seemed to originate from the developed world. A notable lack of activity was observed for the subtopics “advances in selection theory, including experimental demonstrations” (0 of 7 contributions), “selection using molecular information” (1 out of 39 contributions) and “design of selection schemes exploiting additive and/or nonadditive effects” (0 out of 8 contributions). Within the “special topics” category, scientists from developing countries contributed to the subtopics of “animal breeding and the environmental challenges” (22.2% of 9 contributions) and “education and training” (14.3% of 7 contributions). Overall scientist groups from the developing world contributed 41 out of 475 papers during concurrent sessions, or 8.6% of the total number of papers. Developing countries contributing three or more of these papers were Brazil (8), South Africa (5), Iran (4), Israel (4), and Kenya (3).

The contributions of scientist groups from the developing world to the poster sessions are much more evident (Table 14). About half of the posters on the topic “species breeding” originated in the developing world, while between 27.8% (genetics of trait complexes) and 32.7% (breeding objectives and economics of selection schemes) of contributions were made by scientist groups in the developing world. Both posters on special topics were presented by scientist groups of the developed world.

Subtopics with more than 30% contributions from the developing world are listed next. The contribution of the developing world to posters on the topic of “species breeding” amounted to 73.7% for “poultry breeding” (of 19 contributions), 71.4% for “beef cattle breeding” (of 42 contributions), 62.5% for “small stock breeding” (of 16 contributions), 58.7% of “dairy cattle breeding” (of 46 contributions), and 38.5% for “aquaculture” (of 13 contributions). When the topic “genetics of trait complexes” was considered, it was found that posters originating from the developing world exceeded 30% for the subtopics “growth, development, feed intake and efficiency” (55.6% of 18 contributions), “lactation” (42.9% of 7 contributions), and “behavior” (33.3% of 3 contributions). Under the topic “methods and tools,” the contributions of scientists from the developing world exceeded 30% for “functional genomics and systems biology” (37.5% of 8 contributions), “statistical methods – linear and nonlinear models” (33.3% of 15 contributions) and “software and bioinformatics” (33.3% of 6 contributions). When the topic of “genetic improvement programs was considered, contributions from developing world exceeded 30% for “breeding objectives and economics of selection schemes” (50% of 10 contributions) and “management of genetic resources” (33.3% of 15 contributions). It is evident that scientists from the developing world were more likely to make their contributions by the way of posters. It could be by own choice in many instances, while the available slots for oral presentations could simply have been filled by

contributions from developed countries in other cases. Of the 142 posters presented by scientists from the developing world, five or more posters were contributed by Brazil (57), China (17), Mexico (14), South Africa (12), Iran (11), and Kenya (5). The overall contribution of developing countries thus ranged from 11.5% for the topic “special topics” to 31.0% for the topic “species breeding” (Table 14).

Of the 837 contributions presented in concurrent sessions or as posters during WCGALP, 183 (or 21.9%) originated from the developing world. Most of these contributions were from Brazil (65), China (19), South Africa (17), Iran (15), Mexico (14), and Kenya (8). In total, 1,382 delegates from 60 countries attended the Congress. Of these, 229 delegates (or 16.6%) were from 32 developing countries. Developing countries represented by more than 10 delegates were Brazil (67), China (39), South Africa (19), and Mexico (19). It is notable that the average number of contributions per delegate were $183/229 = 0.799$ for the developing world and $654/1,153 = 0.567$ for the developed world. It thus seemed as if the scientists from the developing world were at least as willing to contribute to the scientific program as their peers from developed countries. Alternatively, a contribution at the congress could be a prerequisite for attendance for many of these scientists, given the limited funds that are available for these scientists (see Fig. 19).

From the foregoing it is evident that the quantity and depth of research in the developing world make it difficult for scientists from these countries to compete with peers in the developed world. Kahi [64] also noted that studies from the developing world were underrepresented at the WCGALP. The fact that science groups in the developing world were much less likely to contribute papers on molecular genetics and genomic selection was also highlighted in the latter paper. More than a third of contributions at the WCGALP reported results of genomic selection [71]. The trend toward an increased investment in genomic selection is discussed later under the section “The technological age.” However, the role of scientists in the developing world is anticipated to decline if they are not able to become involved in this study field. As noted before, the disparity in research funding and the availability of high-quality manpower (Fig. 20) doubtlessly contribute to this finding. However, it is also clear that

a number of dedicated scientists from the developing world (based on the average number of contributions per delegate) still present their research findings at international forums. The capacity for change thus exists with such scientists acting as catalysts for the application of sound scientific applications in the developing world.

The Case for Conserving Animal Genetic Resources

It is estimated that 190 of approximately 7,600 livestock breeds became extinct over the past 15 years [72]. Roughly 60 breeds of cattle, goats, pigs, horses, and poultry were lost in the past 5 years. This section asks whether this should be a cause of concern or not. Moreover, it should be debated whether the livestock breeds of the developed world should be treated as a strategic resource, and if so, why?

As an initial comment, it needs to be stated that the share of the developing world in global animal genetic resources trading is minimal [73]. Detailed records were available for trade flows of cattle semen, live cattle, and live pigs. Data for poultry, small ruminants, and aquaculture species are unfortunately scant. The bovine semen trade is dominated by OECD countries. Bovine semen is mostly exported by the United States (32.6% of the trade), Canada (31.5%), the Netherlands (7.4%), France (6.2%), Germany (5.6%), the United Kingdom (3.8%), Italy (2.5%), and other OECD countries (9.2%). In contrast, the share of developing countries in bovine semen exports is minimal at just over 1% of global trade. Developing countries exporting bovine semen are South Africa (0.5%), Argentina (0.3%), Brazil (0.3%), and others (0.2%). Much the same situation is in place for live cattle for breeding, where the contribution of the developing world amounts to only 7.5% of the global trade [73]. The contribution of the developing world to the trade of live pigs for breeding amounts to approximately 5%. The bulk of gene flow in farm animal genetic resources takes place between developed countries (60–70%). The rationale is that farming in these countries developed to depend on high-performance operations, operating at high levels of intensity and accuracy and at a reduced environmental variability [73]. It is argued that farm animal genetic resources from these systems should be adaptable to production systems worldwide. Based on this assumption, it is not surprising that gene

flow from the developed countries to the developing countries constitutes the second most important trade pathways, accounting for between 20% and 33% in the trade of farm animal genetic resources. The exportation of genetic material from the developing world to the developed world constitutes between 1% and 2% of the global trade. There is also modest trade in farm animal genetic resources among developing countries, particularly with reference to low-input production systems [73].

A number of instances where genetic material from developing countries has been introduced to developed countries were reviewed by Blackburn and Gollin [74]. Neither Chinese Meishan pigs nor Zimbabwean Tuli cattle were able to penetrate the commercial livestock market in the United States. Although the Meishan pigs were prolific, unwanted growth and body composition traits led to a realization among pig geneticists in the United States that they could select for prolificacy within local pig breeds, without a need to cater for the unwanted characteristics of the Meishan. Tuli cattle similarly did not perform satisfactorily in terms of growth and feedlot performance, despite a good ranking for biological efficiency compared to Angus/Hereford cows. Interest in the breed thus dwindled, with only 150 registrations in 2000. In contrast, the South African Boer goat gained a foothold in the commercial goat market based on an improved body size, faster growth rate, and an improved conformation compared to local Spanish goats, which formed the basis of United States chevron production prior to the importation of Boer goats [74]. Adoption of the breed is supported by ~45,000 registrations in 2005, but Boer does were found to have a lower reproduction capacity than Spanish and Kiko does [75].

Against this background, it does not seem as if farm animal genetic resources of the developing world have a major role to play in the high-output production systems of the developed world. It even seems worthwhile to consider replacing the relatively low output farm animals of the developing world with more productive genotypes from the developed world. However, it has clearly been shown that these genotypes do not always perform according to expectations because of susceptibility to heat conditions [53–56], and typical diseases [24, 26, 37, 38] in the developing world. The often unpredictable environmental conditions inherent

to farming systems in the developing world also contribute to a lack of adaptation of exotic genotypes [16, 19] under typical farming conditions in the developing regions. Samdup et al. [76] recently established that the crossing of indigenous dairy cattle in Bhutan with high-yielding Jersey cattle, as well as purebred Jersey cattle, resulted in a milk off-take of 2.4–4.6 times that achieved by local cows. However, the higher production levels of Jersey and Jersey crossbreds were offset by poor survival as well as low reproduction rates. Although crossbreeding contributed to higher livestock gross margins in the intensive areas, it has not yet resulted in meeting the demand for dairy products in Bhutan.

The downside of uncontrolled crossbreeding in farm animal genetic resources in the developing world is that the valuable adaptation traits like disease resistance may be lost. Based on the analysis of microsatellites, there is evidence that the genetic basis of the gastrointestinal nematode-tolerant Red Maasai breed is being eroded by crossing, predominantly with the exogenous Dorper breed [17, 77]. Based on the results of Baker et al. [37, 38], the ability of the Red Maasai to tolerate internal parasites may be lost in this way. Urgent intervention to halt the process has been advocated by Ole Kwallah et al. [77]. Fortunately, a nucleus flock under governmental control is still available to use in this process [17]. When Scholtz et al. [78] surveyed the South African beef cattle population in the communal sector, a high percentage (35%) of bulls that were used for breeding purposes were classified as nondescript or crossbred. This classification included the highest percentage of bulls, followed by the Nguni (22.5%), Brahman (18.2%), Afrikaner (9.9%), Bonsmara (5.1%), Drakensberger (2.8%), Simmentaler (2.1%), and various other breeds (4.4%). This observation also draws attention to a possible loss of genetic diversity because of random crossbreeding in the communal resource herds.

In this context, it is important to draw attention to fears that global livestock biodiversity will be compromised by the present animal breeding practices. These fears are supported by many breeds in different parts of the world with a lack of complete population data, as summarized in Table 15. It is clear that population data are not available for many breeds in the developing regions. Among the developing countries,

Breeding in Developing Countries and Tropics.**Table 15** The percentage of breeds with population data in the respective world regions according to class (*Mammalia* or *Aves*), and in total

Region	<i>Mammalia</i>	<i>Aves</i>	Total
Africa	32.5	21.4	30.5
Asia	55.9	41.4	52.5
Europe and the Caucasus	67.2	58.4	64.6
Latin America and the Caribbean	12.9	13.7	13.1
Near and Middle East	42.5	23.3	39.3
North America	61.3	97.8	69.3
Southwest Pacific	22.1	15.2	20.4
World	47.2	44.2	46.5

Source: Adapted from Cardellino and Boyazoglu [79].

information for Asia does not lag as far behind the developed world as for other developing regions, like Latin America and the Caribbean. The implication of this is that conservation status of many breeds is doubtful, simply because there is no information. According to Cardellino and Boyazoglu [79], the risk of extinction is not known for 30.0% of cattle breeds, 33.8% of goat breeds, 30.4% of pig breeds, and 29.6% of sheep breeds. Between 3.1% (goat) and 18.9% (pig) of breeds in all these species are already extinct, while between 12.7% (sheep) and 18.0% (pig) breeds are classified as at risk. The classification of no risk applies to 38.1% of cattle breeds, 49.5% of goat breeds, 32.6% of pig breeds, and 44.9% of sheep breeds. Against the background of these realities, it is important to consider *ex situ* conservation in the form of embryos and semen in some cases [80, 81]. The Brazilian animal germplasm bank has 60,000 doses of semen, more than 250 embryos, as well as over 700 DNA samples at present [81].

It is hypothesized that biodiversity in farm animal genetic resources is needed to ensure that it is possible to react to major changes possibly brought about by major events, like global warming. Against this background, a plan was drawn up to conserve the existing animal genetic resources, and to ensure that adapted genetic resources remain available for the smallholder systems typical of the developing world [82]. In

accordance with this quest, Villanueva et al. [83] developed an indicator of farm animal biodiversity. The system was applied to British sheep and cattle breeds, and allowed inferences that the biodiversity in cattle at least actually increased from 2001 to 2008. A similar trend in sheep was negated somewhat by an increased variability in the data. It has also been reported by Djemali et al. [84] that the Sicilo-Sarde Tunisian dairy sheep breed has actually been resurrected in the recent past, after having been on the verge of extinction.

These arguments lead to the important topic of conserving farm animal genetic resources in the developing world. According to Cardellino and Boyazoglu [79], such efforts should incorporate the recording of phenotypic performance in local breeds. According to the latter authors, the use of molecular information has possibly been overemphasized in conservation efforts of genetic resources in the developing world in the past. The role that molecular characterization may play in the conservation of farm animal genetic resources is well understood, and described by Toro et al. [85]. The point made by Cardellino and Boyazoglu [79], however, is that efforts for animal breeding for the genetic improvement of populations have been compromised to some extent. The basic principles of recording phenotypic data and pedigree information in livestock production systems have been known for a long time [86], so there is no need to elaborate on this. However, this is not done on a routine basis in the developing world. While major gains have been achieved in livestock production systems in the developed world, the same cannot be said for the developing world. Aspects like routine recording of phenotypes and pedigrees become a major effort under communal and smallholder production systems [79]. This results in little genetic gain being achieved. This may be a blessing in disguise, as there are many burning questions in this respect that still need to be answered [79]. Some of these questions pertain to the following:

- Standard interventions aimed at improving production may be counterproductive.
- Genetic and environmental effects may not be adequately researched in harsh environments.
- The magnitude and direction of genotype by environment interactions in unfavorable environment may differ from those in good environments.

- All the crucial adaptive traits may not be recognized.
- Selection could move populations off their adaptation equilibrium and make matters worse.

These challenges should be addressed before major interventions are applied. There are thus a number of research opportunities to address these challenges in future [79]. Before these can be addressed, however, it is necessary to have a closer look at the successes and failures of programs that were implemented in developing countries in the past.

Animal Breeding in the Developing World: Successes and Failures

This section summarizes existing breeding programs, and what could be learned from them. It was attempted to cite most examples from the developing regions, but comparisons with the developed world are unavoidable. Readers will notice that this section is biased toward experience with farm animal genetic resources in South Africa. The reason for this is that a well-developed commercial sector exists in South Africa alongside low-input systems with communal land use. With a producer support estimate of approximately 4% in comparison to the range of estimates from below 5% (in Australia and New Zealand) to more than 70% (in Iceland, Norway, and Switzerland) in OECD countries [8], the South African commercial livestock industry is relatively efficient and in many ways comparable to livestock industries in the developed world.

As a point of departure, it has been established that animal breeding in developed countries has resulted in major and verifiable contributions in improved livestock production, resulting in the demands of consumers being met in a cost effective and sustainable manner [87]. Genetic advances in the more intensive pig, poultry, and dairy industries are often cited as examples of what can be achieved by a structured breeding program for well-defined selection objectives. Recent results pertaining to the well-established Sheep Genetics Australia scheme indicated that participants make progress at an average rate that is comparable to what is attainable in theory in the dual-purpose and terminal sire schemes [88]. Wool sheep farmers are less successful and are progressing at a rate of ~30% of what is attainable in theory. Advances such as those

reported by Swan et al. [88] for dual-purpose and terminal sire sheep breeds have led to selection objectives in developed countries having changed from production traits to traits associated with animal welfare, product safety, and preferences by consumers [65].

It is evident from the foregoing discussion that such advances have not been realized in the developing world. However, there are examples of animal improvement schemes in developing countries that are benchmarked with international schemes. An example is the South African dairy cattle scheme participating in Multiple Across-Country Evaluations (MACE). Test-day databases for the South African Ayrshire, Guernsey, Holstein, and Jersey breeds were harmonized with those of other participating countries [89, 90], to allow participation of the local dairy industry in MACE. Bovine semen produced in South Africa has a small international market share of 0.5% [73].

In contrast, dairy contributed only about 10% to the reason why emerging and communal farmers keep cattle [91]. Communal farmers mostly milked non-dairy breeds like the Nguni (34%), Brahman (22%), Afrikaner (20%), and Bonsmara (10%) under free-ranging conditions. Traditional dairy breeds like Friesians and Jerseys only contributed 3% to communal cattle used for milk production. Herd size averaged 6 for dairy cattle and 11 for dual-purpose breeds. At 16%, the percentage of traditional dairy cows was somewhat higher for emerging farmers, but most of the cows milked were still from nondairy breeds. Herd size averaged 39 head for dairy cattle and 42 head for dual-purpose cattle in this sector [91]. Details of levels of production were not provided but it is assumed to be fairly low. In this respect, McDermott et al. [2] identified the dairy and small stock enterprises in small-scale farming systems as amenable to intensification.

There is evidence that breeding decisions peculiar to regions and managerial capacity of farmers may hold advantages in the dairy production enterprises of developing countries. In this respect, it was demonstrated that the continuous importation of semen may not be economically viable in the Kenyan dairy production system, where smallholders living below the poverty line own 70% of the dairy cattle [92]. Systems where semen from local bulls was used were consistently more profitable than those relying predominantly on imported semen. Arguably this effects

could result from better adaptation to environmental conditions, as more daughters of Kenyan, Israeli, and South African artificial insemination bulls survived involuntary culling under Kenyan conditions [16], as discussed previously. Based on the parameters of the mechanistic lactation functions, it was contended that lower-yielding Ayrshire cows were better adapted to low- and medium-input systems in Kenya than Holstein-Friesian cows [93]. In contrast, the latter breed would have distinct advantages in high-input production systems where the levels of management and husbandry were high. Finally, it should be noted that India became the world's largest producer of milk, mostly through smallholding systems [94]. It is thus clear that substantial quantities of milk could be produced by small-scale farmers. This appears to be the case particularly in countries like Kenya and India, where there is also substantial private sector involvement [94].

The bulk of agricultural land in South Africa is not arable. Large areas are thus suitable only for extensive grazing, mostly by beef cattle in the north-eastern part and by sheep in the southwestern part [8]. The commercial breeding sector of the South African beef industry is serviced by the National Beef Recording and Improvement Scheme managed by the Agricultural Research Council (ARC), as described by Bergh [95]. After a peak of ~450,000 weights in the mid-1980s, this Scheme annually recorded between ~170,000 and ~260,000 weights since 1992. Breeding values for a range of growth/production, size, and reproduction traits are available to breeders [96]. Additional reproduction traits have been developed for inclusion in the Scheme recently [97], indicative of continuous development according to consumer specifications. It is estimated that nine beef breeds (Afrikaner, Beefmaster, Bonsmara, Braford, Charolais, Drakensberger, Gelbvieh, Angus, and Sussex) have at least 80% of the available females participating in the recording scheme [78]. As for other schemes managed by the ARC, real-time information to producers is available on the Internet [95]. Other beef breeds in South Africa are being provided by similar services by Breedplan® International [98], providing a link to international genetics. At 0.8%, South Africa controls a small portion of the international trade in live cattle exports for breeding [73], placing the country in the

third position after Panama (4.1%) and Lithuania (1.0%) among developing countries.

At 47%, the sale of live animals and beef was listed as the most important reason for keeping cattle in the communal cattle sector of South Africa [78]. Cattle were also listed as being important for investment (15.4%) and cultural and ceremonial practices (13.3%), while the production of milk (10.2%), draft power (4.1%), and other reasons (4.5%) were of secondary importance. The average herd size in the communal/emerging sector was 19 head, as compared to 413 head in the commercial sector [78]. The most important attributes looked for a bull by communal farmers were size (33.1%), followed by conformation (22.0%) and performance (18.9%). When ranked by emerging farmers, the attributes were ranked somewhat differently, being performance (30.3%), size (23.5%), and conformation (19.3%). Corresponding attributes in the commercial sector were performance (33.2%), conformation (11.1%), and temperament (9.8%). Only 1.9% of communal and 36.8% of emerging farmers used a controlled mating season, compared to 88.6% in the commercial sector. Artificial insemination was used by 0.1% of communal farmers, 6.3% of emerging farmers, and 21.9% of commercial farmers [78]. Guidelines for the participation of communal farmers to the National Beef Recording and Improvement Scheme are available [99], but uptake is low.

In sheep, across flock genetic evaluation results have been reported for the South African Dorper breed [100], the South African Merino breed [101], and the South African Dohne Merino breed [102]. The South African Small Stock Scheme has recently been compared to the evaluation scheme provided by Sheep Genetics Australia to Australian livestock producers [8]. The schemes do not differ appreciably for the basic production traits (live weights, wool and fiber traits, as well as for reproduction), which are recorded on farm by livestock producers. Differences between the schemes involve traits associated with disease resistance (fecal worm egg counts and traits associated with blowfly challenge) and carcass quality traits (ultrasonic muscle and fat dimensions) which are recorded on a national basis in Australia, but not in South Africa. The personnel to record these traits are not available in the South African scheme [8], and it is therefore only recorded in experimental flocks. The shortage in

qualified personnel is not unexpected if the trend in terms of researchers are compared (Fig. 20 and Table 13). Australia boasts 8.5 researchers per 1,000 community members, compared to 1.5 researchers in South Africa. With almost a sixfold advantage it is not surprising that the former country has the capacity to allow the recording of the additional traits on a national basis. Moreover, if it is considered that the investment in research on animal production and animal primary products constitutes only 2% of the national research budget in South Africa [67], it is clear that scientists in South Africa are under immense pressure to deliver services comparable to that in developed countries like Australia.

Still there is reason for positive thinking. Overall, the South African scheme recorded ~81,000 weights and ~33,000 wool records (including a fleece testing service) for 2006-born animals with four professional staff and 10 auxiliary staff [103]. It was also shown that the recording of weights increased by about 50% from 2003 to 2006 in the scheme. These records were derived from 13 breeds, but slightly more than half came from the two major wool breeds (Merino – 31.4% and Dohne Merino – 23.9%) and a further quarter from the Dorper meat breed (24.2%) [8].

Sustained improvements in the relative economic value of breeding animals have been reported in the South African Merino breed [101] and in other South African breeds [103]. Leading studs in almost all breeds showed additive genetic gains comparable to those achieved elsewhere in the world. It is important to note that similar sheep breeding schemes are operative elsewhere in the developing world. Across-flock breeding values are thus available on the Internet for several

sheep-producing countries in South America (see review by Cardellino and Mueller [104]). Similar reports were forthcoming from developing countries in South America, Western Africa, and India [105]. Kosgey et al. [18] reviewed a number of small stock projects in the tropics. Objectives strived for mostly involved growth, live weight, disease resistance, and traits associated with reproduction. An Indian project that was highlighted, involved the introgression of the fecundity gene from the Garole breed into the Deccani breed. Failed programs mostly lacked farmer participation [18]. Predicted rates of genetic gain from simulations in Ethiopian sheep breeds were generally in good agreement with actual responses in on-station research [106]. These predictions are in the process of being validated in four communities from different Ethiopian agroecological systems, based on community participation. Traditional Brazilian sheep breeding systems generally used appearance as the main criterion for selection. Recently a recording and genetic evaluation scheme named Ovigol® was launched to provide progressive breeders with the option of selection for traits linked to the profitability of their operations [107]. Uptake during the first 18 months was good, with records of 5,195 performance recorded animals of 13 breeders having been entered into the system.

The genetic merit of rams from the South African commercial sheep breeding sector was compared to that of the communal sector on commercial and communal properties [108]. Fleece weight of progeny from commercial rams exceeded that of communal rams by about 15%, while the fiber diameter of lambs sired by communal rams was between 7% and 9% broader than that of commercial rams (Table 16). This resulted in

Breeding in Developing Countries and Tropics. Table 16 Relative performance of commercial and communal rams on properties in the commercial and communal areas of South Africa

Trait	Commercial properties		Communal properties	
	Commercial rams	Communal rams	Commercial rams	Communal rams
Clean fleece weight (kg)	2.8 (100)	2.4 (86)	2.0 (100)	1.7 (85)
Fiber diameter (μm)	18.4 (100)	20.0 (109)	19.4 (100)	20.5 (107)
Clean yield (%)	76.3 (100)	68.5 (90)	66.9 (100)	60.5 (90)
Wool income (ZAR/head)	92.67 (100)	60.09 (65)	54.87 (100)	37.53 (68)

Source: Adapted from Marais [108].
Figures in brackets are expressed as a percentage of performance of commercial rams.

wool income from the progeny of commercial rams being about 35% higher than that of lambs sired by communal rams. This trend was fairly consistent at both localities, with performance at the commercial properties being improved relative to that at communal properties.

In another study, Marais [109] studied the reproduction of ~1,200 communal ewes on four locations either mated to commercial or communal rams under communal production conditions. Reproduction was low, with the lambing percentages (lambs born per 100 ewes mated) being 30% and 47% for ewes mated to commercial and communal rams respectively. The corresponding means for weaning percentage (lambs weaned per 100 ewes mated) were 27% and 37% respectively, while lamb survival (lambs weaned per 100 lambs born) averaged 88% and 79% respectively. It is clear that reproduction of ewes mated to communal rams were substantially better than that of ewes mated to commercial rams, while the progeny of commercial rams had a slight advantage in terms of survival. The poor mating performance of commercial rams possibly suggest that they were not adequately adapted to the low-input communal conditions. The progeny of commercial rams were 7.2% heavier than those of communal rams at an age of 7 months. Lambs marketed per 100 ewes mated averaged 34.2% in a Western Cape study on properties of emerging farmers, with ranges between 9.5% and 56.7% [110]. In contrast, lamb marketing percentage ranged from 90% to 116% in a study where five commercial Merino-type ewe lines were mated to Dormer or Suffolk rams in a terminal crossbreeding experiment [111]. Even if it is considered that no replacements were kept in the latter study (ewe replacements need to be bought in) the improvement is evident. Additionally, the percentage of lambs docked per 100 ewes mated (range in brackets) on commercial properties in the Western Cape amounted to 88% for Merinos (63–103%), 93% for Dohne Merinos (76–113%), and 113% for South African Mutton Merinos (105–124%) in the study of Fourie and Cloete [112]. Even if losses between docking and marketing are considered, it is evident that reproduction on commercial properties would be superior to that on communal properties.

Based on the above information, the South African wool industry embarked on a program to improve

conditions in the communal small stock production areas in the Eastern Cape in the early 2000s. The dual focus was on the upgrading of existing communal shearing sheds as well as the genetic improvement of the local animal resources [113]. Approximately 20,000 breeding rams have been introduced from the commencement of the program in 2003. It was furthermore independently established that 28% of such communal sheds realized prices of better or equal to the national average in 2008/2009, compared to 9% in 2005/2006. Socioeconomic studies also indicated that undernutrition of children in the region was reduced from 43% in 2004 to 28% in 2009. This change results from an improved product (meat and wool) income, which initially contributed 47% to total household income compared to 65% at present.

As pertaining to substitution of animals from a local population with animals from the same breed but from another region to ensure a higher output, it was shown that Turkish Awassi dairy sheep had an improved milk yield compared to local Awassi ewes maintained in Syria [114]. Crossbreeding with and substitution by Turkish breeding stock were thus advocated as avenues for the improvement of Syrian dairy sheep breeding stock. Selection based on performance in the current flock also resulted in immediate gains, demonstrating that these principles are robust for extension to the Syrian environment.

The performance testing of meat and dairy goats in South Africa and other regions were reviewed by Olivier et al. [115]. The bulk of meat goat weaning weight data was derived from the Boer goat breed, with 11,679 records. The vast majority of dairy goat lactations were derived from the Saanen breed, with 14,688 out of a total of 16,148 lactation records. Data from these two breeds (Boer and Saanen) combine pedigree information and performance and form part of the National Livestock Improvement Scheme in South Africa. A study of small-scale goat keepers revealed that uncontrolled mating practices were followed by 98.3% of communal farmers and 92.3% of emerging farmers, at respective doe to buck ratios of 11:1 and 30:1 [116]. The reasons for keeping goats in the communal sector were for cash or investment (43.0%), products (37.6%), and cultural purposes (18.7%). Corresponding figures for emerging goat farmers were, respectively, 34.4%, 40.7%, and 24.8%.

Communal farmers mostly kept unimproved veld goats (53.3%), Angora goats (28.3%), and Boer goats (15.4%). Emerging farmers had a lower percentage of unimproved veld goats (1.0%), and more Angora and Boer goats (62.8% and 36.1% respectively). Flock sizes ranged from 9 to 29 in the communal sector and from 18 to 91 in the emerging sector. High mortality of kids and females was listed as a major constraint to goat farming in these sectors [116].

The South African commercial poultry industry is highly industrialized, with little information on performance in the public domain. It would suffice to say that approximately 16 billion ZAR out of a total livestock income of 37 billion ZAR was derived from this sector in 2005/2006 [8]. In contrast, the communal sector kept an average of 10.9 chickens per household, with a range from 9.7 to 17.0 [117]. The number of hens per household averaged 6.1, with ranges from 5.4 to 8.4. Chicks per household amounted to 1.3, with ranges from 1.0 to 2.3. Egg output was estimated at between 35 and 45 eggs per hen per year. Chickens were mostly kept for household meat (89.8% of cases) and eggs for home consumption (64.2% of cases). Minor reasons for keeping chickens were for selling to other parties, ceremonies, culture, and manure [117]. Indigenous chicken production is considered important throughout Africa, despite relatively low levels of output [118]. However, the latter reference still demonstrated significant genetic variation in egg weight and body weights to be exploited in well-designed breeding programs. Genetic progress can thus be achieved, even though production conditions are less than optimal.

Based upon arguments presented under the previous headings, it was expected that animal improvement in most of the developing countries will be constrained by a lack of capacity. However, success in the commercial livestock sector of South Africa and in other developing countries has been reported above. Relative information on small-scale farming operations in South Africa is also reported for comparison. The latter production systems are comparable with small-scale production elsewhere. However, it is clear that commercial successes are not common in such systems. Production is mostly focused on home consumption, while levels of production are relatively poor. Yet successes have been reported throughout the world, as reviewed by Kahi et al. [119]. Moreover, socioeconomic

drivers leading to success in these case studies were listed by the latter study. These guidelines could be used as a blueprint for future schemes wanting to embark on successful breeding programs in the communal livestock resource.

From the foregoing it seems that sustainable animal genetic resource management is feasible in the developing world. Strategies to operate within the constraints imposed by capacity problems and other limitations in this region need to be considered, while the improvement of production in small-scale, low-input systems should receive serious attention. It is suggested that this will be easier to achieve in the presence of a strong commercial sector.

The Technological Age

It is common knowledge that the available technology improved rapidly over the past couple of decades. Analyses on animal breeding and genetics data that required a mainframe computer 20 years ago for a series of single-trait analyses are now routinely run as a single multi-trait analysis on a laptop computer.

Data Capturing, Analysis, and Dissemination

Computing power and data storage capacities increased markedly over the past few years. Software for the on-farm capture of animal records is readily available. This software enables operators with only basic computer skills to effectively collect data for entrance in national or regional databases. The recording system can easily be managed to use open-source software for routine data entry, data editing, and genetic analyses [120, 121]. Custom-made software for a specific enterprise can also be used for routine recordings [122]. Moreover, excellent research tools for data manipulation, the assessment of environmental effects, genetic parameter estimation, as well as the computation of animal solutions are readily available [123–126]. It seems quite feasible to adapt existing software used for breeding value estimation to include a genomic relationship matrix for the estimation of genomic breeding values in a single step approach [127, 128]. The available software packages allow for the analysis of various traits, which could consist of normally distributed linear data or traits with more challenging distributions (for instance, binary traits

or discrete scores with multiple thresholds) in single- or multiple-trait analyses. The partitioning of random effects in direct and maternal genetic components as well as maternal permanent environmental effects have also become commonplace, while standard genotype by environment interactions is easily modeled. Analyses of longitudinal data, for example, growth data, lactation test-day records or reaction-norm analyses to model genotype by environment interactions, by using random regression methods have also become routine [129–132]. Interactive systems, where participants can access information on their animals directly from the Internet, have also become commonplace [95, 104, 121]. As this process takes place in real time, delays are effectively dealt with. This infrastructure is at the disposal of all livestock producers, including those of the emerging/communal sectors, provided that all relevant information is recorded.

Genomic Selection

If progress can be considered as rapid in computer support systems and specialist software for genetic analysis, this probably applies in the superlative to progress in DNA-based marker systems and marker-assisted selection. The bovine genome has recently been completely mapped and allows the study of the genetic structure of cattle breeds worldwide [133]. High-density Single Nucleotide Polymorphism (SNP) chips of thousands of SNP markers evenly spaced across the genome are readily available for pigs [134, 135], sheep [136, 137], cattle [138–140], and poultry [141, 142]. It has indeed been suggested that full genome information may become as commonplace as SNP technology at the next WCGALP to be held in Vancouver in 2014 [143]. The utilization of the genomic information linked to phenotypes has recently been reviewed by Goddard et al. [144], to give an overview of methods and the future of the technology. Information on SNPs was used in a BLUP or BayesA framework to attain genomic breeding values for Australian progeny testing sires [145]. Compared to the tradition sire pathway EBV, the BLUP-based system improved the accuracy of selecting dairy sires for progeny testing from 0.38 to 0.44 for the Australian selection index, from 0.35 to 0.53 for the Australian profit ranking, from 0.28 to 0.45 for protein yield, from 0.20 to 0.29 for protein

percentage, and from 0.16 to 0.18 for fertility. The BayesA method resulted in further improvements of 0.04, 0.02, 0.03, 0.05, and -0.04 , respectively [145]. There is consensus among analysts that genomic information can greatly enhance genetic progress in dairy cattle breeding [144, 146–148]. However, it needs to be stated that price considerations at present will only allow males and elite females to be genotyped [147]. Naturally, this may change in future as the technology becomes more affordable.

The above advances will have a marked impact on animal breeding in the developed world. The question remains if it will become sufficiently affordable for routine use in the countries of the developing world, given the financial constraints in these countries (Fig. 19). The human capacity needed to make full use of these innovations is another topic that needs to be debated, given the dearth of people with adequate scientific training in these countries (Fig. 20). These and other issues will be debated in the next section.

Future Directions

Future of Livestock Breeding in the Developing Regions and Tropics

Breeding Objectives Given the environmental challenges faced by animals in the developing world and the tropics, there is little doubt that elements of adaptability, robustness, and fitness should form part of the selection objective in those areas. Fitness and/or adaptability can be defined in many ways as was reviewed by Barker [149], but a definition like “a measure of the ability of an organism to survive and reproduce in a particular environment” is probably a good compromise. Naturally, the concept includes stressors that are inherent to the particular environment maintaining the animals, for instance, climatic conditions and disease. As the prospects of breeding for resistance to disease as well as adaptation to stressful environments in terms of heat, water scarcity, and a variable food supply have already been discussed, they will not be revisited here. It is, however, important to mention that records pertaining to susceptibility to a disease are highly incidence dependent [150], which should be considered during analysis. The importance of assessing the genetic resources from the developing world and the tropics for disease resistance has been highlighted by

Gauly et al. [151], while some guidelines as to how to proceed with the process were also presented. Bath and Van Wyk [152] recently proposed a practical check for helminth infestation of small ruminants, which was easily applied by both commercial and small-scale farmers. It was suggested that this check can be used to guide decisions pertaining to the selective treatment of animals for internal parasites.

The remaining elements of fitness are therefore survival and reproduction, as was defined by Goddard [153]. According to the latter author, these elements of fitness have largely been ignored during selection of farm animals, despite obvious economic value. Arguments against reproduction and survival are a low heritability, while it was also considered difficult to record. Reproduction is also sex-limited and usually assessed later in the life of animals than other production traits. The omission of including fitness traits in the breeding objective led to a general decline of fitness in those farm animals that were intensely selected for (say) milk production. Yet the genetic coefficient of variation of 6-week pregnancy rate in dairy cattle equals that of milk yield [153]. The latter author suggests that the correct way to handle this situation would thus be to include fitness traits together with the traits of interest for a particular livestock species in a selection index, with appropriate economic weights.

It is also appropriate to consider selection for reproduction and survivability in a number of livestock species farmed with in developing countries. A number of indicators of reproduction (days from calving to first service, days open, artificial inseminations per conception, and pregnancy rate) in South African Holstein cattle of 14 herds were considered by Muller et al. [154]. Heritability estimates ranged from 0.06 to 0.08, as was also reported by other authors from developed countries. Selection for number of lambs weaned per ewe mated of South African Merino ewes (a trait with a similar low heritability as that quoted above) resulted in a genetic response of $\sim 2\%$ per annum, which is of the same magnitude as is expected for other traits of economic importance [155]. This realized improvement was consistent with expectations based on the review of Snowden and Fogarty [156]. Stayability of South African Angus cattle was similarly shown to be heritable [157]. From these results from the developing world it is evident that selection for reproduction and

herd life in farm animals should be attainable, should it be desired. Appreciable progress has in fact been demonstrated in the national analysis of the South African Merino breed [101]. Total weight of lamb weaned per ewe mated (as measure of reproduction) improved at a rate of 0.73% per annum in the best performing flock, while the average flock gained at 0.14% per annum. At the same time, fiber diameter was reduced by 0.48% per annum in the best flock and by 0.42% per annum in the national flock. During the same period, relative economic values increased by 2.80 ZAR per annum in the best performing flock ($R^2 = 0.94$) and by 1.17 ZAR per annum in the national flock ($R^2 = 0.98$).

How to Achieve the Objective of Improving Fitness and Adaptability

Having discussed the state of animal agriculture in the developing world, as well as successes and failures of projects in that region, the issue remains whether the capacity to allow sustained improvement in those regions exists. It needs to be stated that research priorities for this venture has been clearly outlined by Cardellino and Boyazoglu [79]. The proposed needs are summarized in Table 17 and include the development of suitable information systems, the characterization of resources, as well as a sound knowledge of genetic diversity, functional genetics, and animal breeding. The collection of phenotypic data is a prerequisite for the system to be successful. If these data could be linked to pedigrees it would be an added bonus. This objective may seem nearly unattainable at present. However, traceability based on individual identification is increasingly seen as a good agricultural practice for the assurance of safety and quality in global trade [158]. It is foreseen that the developing world will in future have to comply with such prerequisites for continued market access. It should thus not be seen as far-fetched to start to apply a principle like individual identification in the near future. Data containing phenotypes linked to pedigree information can initially be used for routine genetic improvement. If it is affordable it could also be linked to genomic information in future. Goddard et al. [144] stressed the importance of being able to link genomic information to phenotypes for the accurate prediction of genomic breeding values. It should be noted that recommendations on animal welfare have been left out from Table 17 as it will be dealt with separately at a later stage.

Breeding in Developing Countries and Tropics. Table 17 Research priorities to enable the breeding of livestock in developing regions to increasingly contribute to local food security and poverty relief

Area	Specific needs
Information systems	Upgrading of the existing farm animal genetic resources (FAnGR) information system
	Acquisition of data on population size and structure
	The geographical referencing of FAnGR
Characterization	Define traits and record adaptation and performance of indigenous populations
	Describe the environment to evaluate genotype x environment interactions
Genetic diversity	Define and determine the risk of extinction for FAnGR
	Adopt measures to halt the decline of genetic diversity
	Assess genetic diversity by using molecular markers
	Integrate data on phenotypes with molecular information
	Acquire global information on specific markers associated with production and fitness
Functional genetics	Ensure that the genetic basis of adaptation traits are properly understood, including disease resistance, fitness, and adaptability to challenging environments
	Apply the most recent tools for conventional genetic improvement and marker-assisted selection (MAS)
Animal breeding	Assess impact of selection under low-input conditions
	Study the consequences of introducing exotic breeds
	Devise breeding structures for a low impact environment where little or no organizational structure exists
	Research stable crossbreeding systems with a role for indigenous breeds
	Implement MAS selection where applicable, that is, in the case of disease resistance
	Gain insight in genetics of adaptation to systems with a low and variable nutrient supply

Source: Adapted from Cardellino and Boyazoglu [79].

The challenges of such a venture will be enormous. The requirements and structure of performance recording and genetic evaluation for low-input agriculture have been well documented [159] but their application in practice is lagging behind. Open nucleus breeding systems have often been advocated as a solution to the lack of sustainable genetic improvement in the developing regions [18, 160]. This solution will only be feasible if the nucleus herds/flocks are under central control of accomplished scientists at a governmental, academic, or parastatal research institution. Having said this, it is equally important to have the support of the stockowners at grassroots level. Failure of livestock breeding projects in the developing world has commonly been attributed to a lack of

community involvement [18], whereas successful efforts generally benefitted from community involvement [119]. The importance of close involvement with the community stems from the multifunctional role of livestock in communities in the developing world [94]. Broad stakeholder involvement has been suggested, with collaboration of local committees, researchers and development practitioners [161]. Close interaction of these diverse partners are considered to be critical for success. The importance of participatory development approaches was also stressed by Nesamvuni et al. [162]. According to the latter authors, the integration of coexisting research and development programs is highly preferable to research and development programs operating in isolation.

Using the Kenyan Boran breed as an example, Rewe et al. [163] assessed open and closed nucleus systems of registered breeders with or without gene influx from commercial breeders to ensure that adaptation traits (mainly disease tolerance) are not compromised. The introduction of germplasm from the commercial breeders was profitable in both schemes. The study demonstrated that the success of a breeding program depended on the production system, and that adaptation could be introduced from the indigenous herd, as was suggested in Table 17.

It will be a bonus if a strong commercial sector, operating on par with conditions in the developing world, can be included in the genetic evaluation system. The successful establishment of public–private partnerships to enable the system to work is a further prerequisite for success. This blueprint seems to be effective in the South African small stock sector, as was described previously. It also appears to be relevant to dairy production in Kenya [94]. The real success with it will, however, only become known with the passage of time.

It needs to be stressed that this whole process can be orchestrated with existing tools for quantitative genetics, using known theory for the sustained genetic improvement of livestock. The emphasis on fitness traits may depart slightly from what has been practiced traditionally. Yet the approach to select for adaptation and fitness would be fairly similar to what has been proposed by Goddard [153] for general application across the globe.

Table 17 also refers to the possible role that crossing with indigenous livestock may play in commercial production. The benefits of well-planned crossbreeding systems in terms of direct and maternal heterosis are well known [164]. Structured studies are needed to apply these to livestock breeds in the developing world, where it needs to be balanced with the need to conserve the indigenous genetic resources. The substantial differences between breeds that form part of the genetic resource, as well as the relative advantage of crossbred ewes under challenging conditions in France compared to purebreds was confirmed in the literature [165, 166]. More structured research on this topic is needed for the optimal utilization of local, adapted farm animal genetic resources in the developing world. The role of cortisol and the functioning of the hypothalamic-pituitary-adrenocortical axis in

breeding for an increased robustness have been highlighted recently [167]. Future studies should thus focus on the underlying causes of genetic variation at this level.

It is also important to consider the role that molecular genetics and marker-assisted selection may play in this process [167]. Constraints in monetary resources, infrastructure, and suitably qualified scientists place immediate earth-shattering breakthroughs beyond the ability of developing countries at present. Further issues like intellectual property rights also complicate immediate application on a wide scale in the developing world [168, 169]. However, scientists in the developing world should take cognizance of progress in the application of marker-assisted selection in the developed world. The rapid development of technology may allow for inputs from this part of the world in future, as the technology becomes more affordable. Fitness traits like disease resistance and reproduction, which need to be selected for in the emerging regions, is particularly well suited to marker-assisted selection [168, 170]. The provision here is that sufficient monetary investment in the genotyping of animals should be available at that stage. Therefore it is also recommended that DNA samples from phenotyped animals in the nucleus flocks/herds be collected and stored for possible future usage. The general concept has been applied in the Australian Information Nucleus flock [171–173], which has already produced a number of outcomes [174]. Scientists in the developing world are well aware of the importance of combining genetic and environmental information for selection decisions [64]. It should thus be feasible for these scientists to adapt to the requirements listed above, should the opportunity arise.

Readers will notice that most of the examples listed in this section involved grazing ruminants. It is conceded that pigs and poultry played an important role in the production of protein in both the developing and developed world, and will continue to do so in the future (see Fig. 13). However, these industrialized livestock systems are in many cases served by multinational breeding companies, as stated previously. Moreover, the prospects of selecting for “robustness” or “fitness” in poultry and pigs have been covered in some detail in other entries in this encyclopedia [175, 176]. The issues dealt with in the latter entries

are complex, and it would have been impossible to deal with them comprehensively in this entry.

Finally, it is clear that the system that is proposed would not only need monetary inputs, but also the human capacity to successfully orchestrate the flocks/herds [119]. In case of severe threat to some genetic resources, the option of ex situ conservation should also be an option [80, 81]. The need for collaboration across institutional and national boundaries, to ensure that the various forms of information generated in this way are optimally utilized, cannot be overstressed [168, 169]. It is therefore appropriate to ensure that the intellectual capacity to drive all the processes is available, as discussed under the following heading.

Broadening the Knowledge Base It is evident that the objectives above are unlikely to be achieved without a sound knowledge base. Based on the disadvantage of developing countries in terms of human capacity (Fig. 20), it is obvious that the people active on research and development of farm animal genetic resources should be well-trained. The limitation in human resources results in several challenges for scientists in this region, such as an increased workload in terms of teaching, and a reduced capacity for conducting research [177]. Sustainable farming and the improved use of farm animal genetic resources were targeted in a joint venture between the International Livestock Research Institute (ILRI) and the Swedish University of Agricultural Sciences. Training by the project team reached 137 university lecturers and researchers in developing countries so far [177]. Agriculture is not a favored study direction, as it is associated with poverty and an inability to improve the livelihood of families. A typical curriculum for students in animal science in South Africa (as an example of a developing country) was provided by Casey [178]. The intention with the training of students is to prepare them for a professional career in animal production, with appropriate registration. It is also noted that Sub-Saharan Africa has many universities that teach animal production. However, there is a lack of communication and collaboration between these role players [178]. In contrast, six European universities joined hands to form the 2-year European Master of Science program in Animal Breeding and Genetics [179]. The intention of the course is to assist in increasing livestock and fish

production, development of sustainable animal breeding programs, the improvement of health and welfare, and the preservation of natural resources. The program also draws students from developing countries, but with ~20 scholarships per year, the impact is limited. Of students starting the program between 2007 and 2009, 46% were from Asia, 31% from Africa, 9% from the Americas, and 13% from within Europe. In Latin America, two universities from Peru, Bolivia, Mexico, and Spain each collaborate with universities in Argentina and Austria to present a master degree in Animal Science [180]. Original assessment indicates that there is heterogeneity in the curricula, grading systems, and duration. A program for harmonization has been proposed.

In view of the challenges listed above, steps need to be taken to rectify the situation in the developing world. The obvious prerequisite is to ensure a skilled and motivated core of senior mentors, to pass on knowledge to the next generation. This will be facilitated by closer collaboration between role-players, both among institutions in the developing world and with institutions in developed countries [64, 119, 168, 169, 177]. Joint appointments of senior researchers at science and technology institutions at higher education institutes could also benefit training in farm animal genetic resources, by making better use of expertise [181]. To assist in these quests, there is a wealth of Internet-based training modules that can easily be accessed [182–184]. Collaboration between research groups and those involved in training is also proposed [177]. This approach will ensure that the studies embarked upon will be relevant. It is also important to attempt to recruit and retain well-qualified and dynamic persons for careers in animal agriculture, both in training and research. The so-called brain-drain from developing countries needs to be stopped and preferably turned around. This will only become feasible if scientists see a future for themselves in animal agriculture in developing countries, both in monetary terms and in job satisfaction. Alternatively, well-trained international scientists could be used as trainers when they return to their home countries for holiday or familial responsibilities [177]. There ought to be opportunities for improving the local knowledge base in developing countries when all these avenues are fully exploited.

“New” Issues

Finally, it is necessary to give attention to issues that have not previously impacted on animal agriculture in the developing world. Both topics are specialized study fields, worthy of an exhaustive discussion in their own right. However, this chapter will only briefly deal with the new challenges, within the developing world context.

Climate Change There is consensus that the global temperatures are on the increase, and that it is probably related to higher atmospheric concentrations of the so-called greenhouse gases. It is expected that global warming will affect extensive pasture systems to a greater extent than intensive, industrialized systems [62]. This implies that animal production in the developing world will be more vulnerable than in the developed world [4]. The carbon dioxide emissions of the developing world, in particular, are modest compared to emissions in the developed world [2]. Hoffman [80] pointed out that livestock production is contributing to global warming, but also that it will be affected by the consequences of the phenomenon. It is estimated that agriculture produces between 10% and 12% of the total global anthropogenic greenhouse gas emissions [185]. Between 50% and 60% of methane and nitrous oxide could be derived from livestock activities. The review by Eckard et al. [185] focuses on the possibility to reduce greenhouse gas emissions by ruminants through the manipulation of the animals, their diet, and their rumen microbes. Manipulation of animals is centered about breeding (the focus of this entry) and on changing managerial systems. Eckard et al. [185] cited sources that quoted differences between animals in methane production, hinting at possible genetic differences. These allegations were substantiated by Robinson et al. [186], reporting that methane production in sheep were repeatable (0.47) and heritable (0.30). Adjustment for live weight resulted in these parameters being reduced to respectively 0.32 and 0.13. Adjustment for live weight also eliminated the effect of sire breed upon methane production, while correlations with rumen volatile fatty acids did not support a contention that the latter could be used as a proxy for methane production. Cassandro et al. [187]

predicted methane production of dairy cows from dry matter intake, and derived a heritability of 0.12, with upper and lower confidence limits of respectively 0.03 and 0.28. Genetic correlations of methane production with milk yield and butterfat content were high (respectively 0.92 and 0.67), but protein content and somatic cell count were not genetically correlated to predicted methane production (0.14 in both instances).

Alternatively, selection for an improved efficiency would also indirectly benefit methane excretions per unit product from ruminants, as reviewed by Eckhard et al. [185], Hegarty and McEwan [188], and Herrero et al. [189], as would improvements in feed conversion and residual feed intake. Lamb production systems based on crossbreeding would be more effective in terms of methane produced per unit product than a wool and hogget production system [188]. Alternatively, methane emissions per unit product could also be reduced by an improved reproduction rate, the early disposal of unproductive animals and the longer retention of productive animals in flocks or herds. As dairy products are produced at lower levels of greenhouse gas emissions than beef, there may be a shift to dairy in a situation where greenhouse gasses need to be reduced [80].

Possibly more relevant to conditions in the developing world is the adaptation of animals to higher ambient temperatures and to more frequent severe climatic events, which are predicted to be a consequence of climate change [80]. The possible genetic improvement of adaptability, robustness, and heat tolerance has already been discussed and will not be reiterated here. Unforeseen catastrophic climatic episodes like floods, droughts, and heat waves could have a major and unpredictable impact on local farm animal genetic resources. For instance a heat wave in 1995 in the Midwestern United States resulted in an economic loss of \$31 million in the state of Iowa alone [62]. Such events should be managed when they occur, as it is impossible to plan for them. However, the need for a disaster strategy to be in place in areas likely to be affected cannot be overemphasized. Thornton and Gerber [4] suggested that up-to-date weather information will play a role in mitigating the effects of climate change. State-supported schemes reminiscent of a sort

of insurance scheme may have a role to play in disastrous events, while species substitution toward more hardy animals may be contemplated (i.e., from cattle to camels in dry parts of Kenya).

Animal Welfare Pressure on output traits, particularly regarding the more intensive livestock industries, resulted in the welfare of farm animals being compromised [189]. This topic is also extensively covered by Knap [175] in this issue, and interested readers are also referred to this paper. Because of this, discerning consumers have ensured that animal welfare is among the important considerations in production systems in developed countries, like Europe [190, 191]. Welfare in farm animals are usually defined as freedom from hunger, thirst, discomfort, pain, injury, fear, and distress, as well as an ability to express normal behavior [189]. Several routine husbandry procedures are considered to infringe on these fundamental freedoms, for example, the Mules operation in Australia [28, 30]. In this case, popular opinion has prevailed that the pain, fear, and distress of the operation outweighs the possible later advantages in terms of better resistance of animals to breech strike. This has resulted in pressure on Australian livestock producers to phase out the procedure. The same reasoning applies to tail docking of lambs. An alternative genetic solution was thus sought to enable the abolishment of this practice in the Netherlands in the two sheep breeds where conditional approval to dock tails are still granted [192]. Genetic variation seems to exist for tail length and selection for shorter tails may thus be possible. Issues in the developed world mostly involve the quality of life of farm animals in more intensive systems [193]. Aspects like survival, adequate nutrition, and protection against intense cold or heat are more important under extensive conditions. Sørensen and Fraser [193] proposed a self-regulatory process of auditing livestock operations for animal welfare, agreed on by all role-players.

Aspects of importance to this discussion are the impact breeding for welfare traits could have on genetic gains in other traits. First of all, it is fair to say that animals, where welfare is compromised, will in many cases not be capable of high levels of production. Because of the emphasis of herd health in dairy cattle

selection schemes in Norway along with production traits, cows are much more likely to reconceive than in European countries. In response to this, longevity as well as health and fertility became much more important in the United Kingdom dairy indexes as well [189, 190]. Impaired mobility of dairy cattle because of poor claw health also leads to direct and indirect costs. Claw health traits of Finnish Ayrshire cows were lowly heritable [194]. Some leg conformation traits had favorable genetic correlations with claw health, and could serve as indicator traits.

A simulation study on outdoor pig production indicated that genetic gains had to be compromised when welfare traits (leg conformation, mothering ability, and longevity) were included in the selection index [195]. Apart from a slightly slower growth rate and a reduced fat depth, free-range pigs performed as well as pigs in a conventional housing system [196]. The former system produced pork of a similar quality as that observed in a conventional system. Observations made at lambing were evaluated as possible indicators of ovine lamb survival by Brien et al. [174] and Lemmon et al. [197]. Although some observations were favorably related to survival, none were obvious candidates for immediate industry application in the former study. The latter study suggested that alternative methods of improving lamb survival should be investigated. It is however, notable that divergent selection for the ability of sheep to rear multiple offspring led to divergence in age-specific lamb survival in South Africa [198]. Hatcher et al. [199] also reported scope for the improvement of lamb survival by selection, although low direct and maternal heritability estimates were derived.

Animal welfare of the mostly free-ranging animals in the developing world is probably not compromised to the same extent as those animals in more industrialized systems. The exceptions are probably freedom of hunger and thirst, which cannot be guaranteed. It is nonetheless important for scientists in developing countries to take cognizance of the emphasis on welfare, and ensure that information on the impact of the selection strategies for livestock (that were previously discussed) on animal welfare are also considered. Intuitively, selection for adaptability, robustness, and fitness is unlikely to compromise welfare. However, challenge

of animals by environmental stressors (heat, parasites, and uncertain food supply) typical of the developing world may lead to some ethical concerns. It is reassuring that the need to ensure a value system throughout the entire production chain is also recognized in the developing world [200].

Conclusion and Recommendations

From the foregoing it is evident that livestock industries in the developing world are faced by numerous challenges involving the environment, infrastructure, funding, and the availability of a sufficient number of well-trained scientists specializing in breeding and farm animal genetic resources. Despite these drawbacks, scientists in the developing world seem to be willing to contribute to the advancement of science in the region in spite of the considerable odds against them.

Within the constraints in terms of funding and manpower, it is proposed that major efforts should be put into obtaining phenotypic records from the farm animal genetic resource managed in the developing world. Wherever possible these records should be linked to pedigree information, which could follow on from the identification of animals for traceability purposes. Should this vision prove to be impossible to implement on a wider scale, it should be applied to genetic resources maintained by governmental, academic, and parastatal institutions within the developing world. The decision as pertaining to broader community involvement will largely be determined by local conditions, and need to be considered with care on the grassroots level. A prerequisite is that supportive institutional research actions should be conducted in environments conforming to those used by those resource-poor stockkeepers standing to benefit from it. Secondly, it has to be ensured that all initiatives involving the latter groups must have their full support for the intended projects to be successful. This structure will form the basis for simple animal recording and genetic evaluation schemes under communal and emerging farm systems. These schemes are highly unlikely to be cost effective and need to be subsidized from funds supplied by local government, higher education institutions or external sources. However, such evaluation is integral for local food security, sustainable

development, and rural stability, thereby increasing leverage for the acquisition of funds dedicated to this cause. Should the envisaged scheme become successful and gather momentum, it would be easy to integrate into existing livestock improvement schemes for commercial agriculture, should the infrastructure exist.

Being in the developing world and the tropics, breeding should focus on traits associated with fitness and adaptability. However, traditional production and product quality traits should also be recorded, to monitor the impact of selection decisions on these traits.

It is not foreseen that genomic selection will change the way animal genetic resources in the developing world are selected in a drastic way in the immediate future. However, it is advised that samples for the extraction of DNA are acquired for as many animals with phenotypes as possible in the system. After the extraction of DNA, these samples should be kept under safe conditions for possible future use. Given the appreciable advances in the technology, it may be possible to utilize DNA-based methods for the evaluation and selection of farm animal genetic resources in the developing world in the foreseeable future. Should this vision become a reality, the scene should be set for the immediate application of this technology on a broader basis. The need for adequate phenotypic data to link to genomic information cannot be overemphasized.

Finally, it is conceded that new issues such as global warming and the insistence of customers on assurance of traceable and welfare-based production systems are likely to affect animal breeding and genetics in the developing world in future. The animal breeding sector in developing countries should preempt these possible challenges, and react to it in a constructive way. Modern societies embrace change. Animal breeders in the developing world thus need to ensure that the challenges imposed by these issues are turned into opportunities.

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Breeding in Horses

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Article Outline

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Glossary

Animal model (AM) Statistical models that are used for evaluation of breeding values of all individuals in the population of interest.

Best linear unbiased prediction (BLUP) Standard statistical method for estimating breeding values in populations. BLUP adjusts for systematic fixed environmental effects and accounts for genetic relationships among animals.

Breeding value (BV) Mean additive genetic value of an individual relative to all members of the (base) population.

Effective population size (N_e) Number of individuals that would give rise to calculated sampling variance, or rate of inbreeding, if they bred in the manner of the idealized population with complete random mating, no selection, no migration, and no mutations.

Estimated breeding value (EBV) Estimate of the mean additive genetic value of an individual for a quantitative trait.

Generation interval (L) Average age of the parents when their progenies that will replace them in breeding are born.

Heritability (h^2) Measures the extent to which the phenotypes are determined by genetic factors. It is expressed as the ratio between additive genetic variance and the total phenotypic variance.

Inbreeding coefficient (F) Measure of the probability that two genes at any locus in an individual are identical by descent. It refers to an individual and expresses the degree of genetic relationship between the individual's parents.

Riding horse The narrow definition of riding horse or sport horse refers to horses of “Warmblood” breeds or Thoroughbred crosses, which compete in the classical equestrian sporting events of dressage, show jumping, and eventing. However, the broad definition of a riding horse refers to a horse used for any type of riding and will be used here.

Selection Any natural or artificial process favoring the survival and propagation of certain individuals in a population.

Selection intensity (i) Function of the proportion of animals selected for breeding relative to the total number of animals available for selection.

The smaller the proportion selected, the higher the selection intensity.

Timeform handicap ratings An estimate of racing capacity of Thoroughbred horses (in Great Britain). Express racing merit as weights in pounds that the compiler believes the horse should carry in an average free handicap race.

Trotter A horse trained for harness racing. The horse races in trot, which is a two-beat springing gait with a suspension phase (no ground contact) between two diagonal supporting pair of legs.

Definition of the Subject

Animal breeding can be defined as a human activity with the deliberate purpose to change existing populations of animals in some desired directions, so that future generations of these animals become more valuable in some sense. A prerequisite for successful animal breeding is that there is a genetic variation in the population in the traits one want to improve in future generations. Other requirements are: clear definitions of the breeding goals, good pedigree files, valid measures of the desired traits, methods of genetic evaluations that can combine information from the pedigree and the measured trait, and finally effective selection of breeding animals with high estimated genetic values (BV = breeding values) and therefore presumably with relatively large proportion of valuable genes affecting the desired traits.

The selected parents will transmit their genes to the next generation, and depending on the amount of genetic variation in the traits, accuracy of estimated genetic evaluations, and the selection intensity, the average level of the offspring generation will be raised as compared with the parent generation.

All general principles and methods of animal breeding obviously apply equally to the breeding of horses. There are however few structural and demographic characteristics specific to horse breeding that should be highlighted:

- Thorough registration of pedigree files
- Low rate of reproduction
- Long generation intervals
- Important traits are recorded on both males and females

- Wide overlapping of age groups among breeding candidates
- Considerable nonrandom mating practiced
- Extremely large differences in economic value depending on assumed genetic merit

All these factors support the use of methods for genetic evaluations that combine all pedigree information in an optimal way. In particular, the use of animal models (AMs) to obtain best linear unbiased predictions (BLUP) for genetic evaluation of breeding animals has become an important tool in modern horse breeding.

Introduction

Humans began to breed horses when the horse was domesticated some 6,000 years ago. Tamable animals were then selected from wild flocks and broken in. Stallions and mares with suitable temperament and desired characteristics were spared and got offspring in their new environment. The fitness measure of natural selection in the wild life was replaced by a selective value in the new role of serving humans. This artificial, and to lesser degree natural selection, of horses over 6,000 years has resulted in gradual genetic changes and subdivision into breeds adapted to different purposes [1, 2].

Throughout the history horses have been used for variety of purposes, such as riding, driving, carrying packs, and pulling agricultural equipments. Horses were also for a long time the most important means of transport in wars and have played a great role in the political and social development of many civilizations and even for the conquest of whole continents. Horses have also played a major role in the mythology of many religions but have as well been kept for their grace and were commonly used as a symbol of material status. The Vikings even used stallions for fighting contests. In many cultures, horses have been used for milk and meat production. The life of nomads in central Asia, of cowboys grazing and driving big herds of cattle, and of Indians hunting wild buffalos on the savannas in North America would have been impossible without horses. In brief, the human history would have been very much different without the company of the horse [3].

Today there are about 60 million horses in the world [4]. While horses are still used for agricultural work

and transportation in many parts of the world, the main role of horses in modern societies is to serve humans as pleasure or sport companions. The economic and social impact of the worldwide horse sector is tremendous and often underrated. In Europe, three to six horses (varies between countries) create full employment for one person. So within the European Union alone, with almost six million horses, about one million people are directly or indirectly employed in horse-related activities. About 4% of European agricultural land is dedicated to horse breeding [5].

Horses are used and will undoubtedly be used in the future for various competitive performance events, sport events, and pleasure riding or driving. Modern knowledge of animal breeding, genetics, statistics, reproduction technology, and computer science will certainly be used for adapting the different horse populations of the world to their intended purpose.

Horse Breeding

Breeds

Horses are members of *Equus ferus caballus*. In fact, there is no strict scientific definition of the term breed, but the elusive concept of breed as a definition of a population of “purebred” animals is commonly used among horse breeders. The classic definition of a autochthonous breed refer to a distinctive set of animals associated with a restricted geographical area in which it was developed to meet human needs under particular local conditions [6]. Often horse breeds are defined by breeding societies or registries that record pedigrees and maintain a studbook for a selected subset of horses based on geographical origin, phenotype, or function [3]. New synthetic horse breeds have been created by genetic selection according to a common breeding goal across several older horse breeds. As an example, many European Warmblood breeds have evolved this way. At the Web site “Breeds of Livestock: Horse Breeds” (<http://www.ansi.okstate.edu/breeds/horses>) detailed description on over 300 different horse breeds all over the world can be accessed.

Breeding Goals

Horse breeding, as all animal breeding, starts with a clear definition of breeding goals that usually includes

many traits. The breeding objectives are a statement of the relative values of genetic change in all the desired traits that are included in a breeding plan. The overall objective (aggregate genotype) can be expressed as $H = \alpha_1 A_1 + \alpha_2 A_2 + \dots + \alpha_n A_n$, where α_i is the relative (economic) weight and A_i is the animal's breeding value for the i th trait. The α_i values are often linear or nonlinear functions of the profit (return – cost) [7, 8]. Horse breeders often have a rather clear idea as to which traits they want to improve by genetic selection. However, the exact definitions of the relative weights on the different traits included in the breeding goal are often vague and determined by preferences of the individual breeder. Meanwhile, it is important that breeders should be provided with genetic evaluations for all the major traits that might be included in the breeding goal [9].

Registration of Pedigree Files

Unique identification of all members of a population has become a prerequisite for all rational breeding schemes using modern animal breeding methodology. The same identification number must refer to the same horse anywhere in the comprehensive pedigree files and in all files containing the registered traits. As horse breeding becomes increasingly more internationalized, the communication between horse registers in different countries is vital for successful breeding schemes. It is important that the identification number given to a newborn foal follow the individual animal throughout its entire life, even if the animal is exported to, or competes in, another country. It should contain codes for the country of birth, year of birth, and possibly the sex of the animal. The Web-based “universal equine life number” (UELN) system (www.ueln.net) offers a solution to this problem.

Measured Traits and Estimation of Genetic Parameters

An important part of a horse breeding scheme is to develop and use measures with good correlations with the traits in the breeding goal. The measurements need to be collected on a large or a random part of the population to be used in the selection and breeding process. Most traits that are important in breeding of horses are governed by a large number of genes and

many environmental factors. They may therefore be analyzed with genetic and statistical methods that apply to quantitative traits [10]. Measurements of performance traits in horses are often not normally distributed and need to be transformed to approach the normal distribution. Sometimes conversion to ranks is more favorable [11]. Measures of performance in racing and other equine competition sport events are frequently based on functions of earnings, ranks, or racing times. Occasionally, the measures are summarized in handicap ratings or cumulated competition points.

In many populations, the recorded traits are scored on a linear scale, often by subjective judgment, in special field or station tests. These traits may involve measurements of conformational details, temperament, performance in special gaits, or performance at various ranch tasks.

Before the registered traits can be used as a basis for genetic evaluations, the genetic parameters (variation, heritability, genetic correlations, and environmental correlations) among the traits must be estimated. The methods used for estimating genetic parameters in horse populations are usually based on maximum likelihood techniques for mixed animal models [12, 13]. In some recent cases, Bayesian Markov Chain Monte Carlo (MCMC) methods have been applied [14, 15].

Heritability of racing performance traits based on earnings and rank functions have frequently been estimated in the range of 0.3–0.4. Time measures in trotter races and shorter gallop races generally show heritability estimates of nearly the same magnitude (0.2–0.4), while heritability estimates of racing time in longer Thoroughbred races are usually considerably lower or in the region 0.1–0.2 [12, 13].

Heritability estimates of competition variables for jumping and dressage performance in riding horses have been found to be lower than in racing or about 0.1, on average. Data on competition results in riding horses is often subjected to strong preselection, which can be the main reason for the low heritability estimates [13].

The average heritability estimates for field test traits measuring gaiting ability and free jumping in riding horses are in the range of 0.2–0.3. Corresponding average heritability estimates of traits registered at station

tests for stallions are generally much higher or in the range of 0.4–0.6 [13].

Heritability estimates of sport competition scores in Icelandic horses were found to be around 0.2–0.3, while heritability of field test traits within the same breed was estimated in the range 0.2–0.4 with the average value of 0.34 [16, 17].

Heritability of cutting performance in Western riding competitions has been estimated in the range of 0.04–0.19 [18].

This brief summary confirms that genetic variation and thus scope for genetic improvement has been found in the most important traits in many horse breeds.

Genetic Evaluations and Selection

Traditionally, selection of horses was for a long time based on phenotypic observations on performance and body conformation in combination with subjective evaluation of the pedigree. Since mid-1980s, the BLUP method with animal model (AM) has gained popularity as a superior and standard method for combining information from phenotypic observations and pedigree [19]. Estimated breeding values (EBVs) obtained by AM-BLUP are now used as the main selection criteria in many horse populations.

Estimation of breeding values in a population begins with definition of a linear statistical model. The model should fit the data as well as possible but it should also include as few parameters as possible. The model should account for all major factors affecting variation in the data in a systematic way. In the simplest form, the model may be written for a single trait as

$$y_{ij} = \mu + b_i + a_j + e_{ij}$$

where y_{ij} is the phenotypic observation on the j th horse belonging to the i th class of fixed (systematic) effects affecting the trait; μ represents the overall mean of the (base) population; b_i represents the deviation from the population mean caused by the i th class of fixed effects; and a_j represents the breeding value of the j th horse. The breeding values are random normally distributed deviations from the genetic mean of the base population and have the variance $\mathbf{A}\sigma_A^2$, where \mathbf{A} is the additive genetic relationship matrix. Finally e_{ij} denotes the remainder of the model, which is assumed to include

independent and randomly distributed environmental effects pertaining to the j th horse.

Practical application of AM-BLUP in horse populations are usually based on far more complicated models than that shown above. They often include many fixed environmental factors, which affect systematically the variation in phenotypic records. As the breeding goal usually includes many correlated traits, multiple trait (MT) AM-BLUP procedures are commonly used for genetic evaluation of horses. Sometimes additional random factors are included in the model. This may be for genetic evaluation of repeated records on the same trait, or in other cases for better estimation and adjustment of genetic or environmental effects. As an example, the model may include both permanent environmental and genetic effects of the dam (maternal effects), or permanent environmental effects of riders, drivers, or trainers. Random regression models as an alternative to repeatability models for genetic evaluation of traits of longitudinal nature have good prospect in horse breeding [20, 21]. The trajectories may for example represent age development, racing distance, or competition classes.

Important traits in horse breeding are commonly scored on an ordered categorical scale. If there are at least several categorical classes and histograms of the distribution show good approximation to the normal distribution then the data can be analyzed by linear models without any significant loss in precision. If, however, there are as few as 2–4 classes, then nonlinear threshold models may be more appropriate. This particularly applies to binary traits with low or variable frequency across the fixed effect classes of the model. But sometimes linear models (AM-BLUP) are used in such cases in large data, since the computations in the linear models are much simpler.

With the AM-BLUP method, the effects of fixed factors and the breeding values are estimated simultaneously by solving a large set of mixed model equations (MME) with equally as many unknown solutions as there are equations. The estimated breeding values become adjusted for fixed effects that are correspondingly adjusted for differences in breeding values of the horses with records in the various fixed effect subclasses. The use of the additive genetic relationship matrix inverse (\mathbf{A}^{-1}), computed from the pedigree list, ensures that sharing of genes between related

animals is correctly accounted for in the model. In addition, the EBVs of animals that are parents of recorded animals are adjusted for in the EBVs of the mate. That is a very important property in horse breeding where the allocation of mares to breeding stallions is generally far from random in terms of genetic merit.

The pedigree file used as data for computing \mathbf{A}^{-1} is a list of all registered animals in the population. Each row consists of unique identification number of the individual animal and both parents. First, the inbreeding coefficients are calculated for all animals with one of the several efficient algorithms (e.g., [22, 23]) that have been developed from the original algorithm of Quas [24]. Then the elements of \mathbf{A}^{-1} are build up by simple rules depending on the number of identified parents of each animal [25]. Animals without identified parents build the base population. In most horse populations, pedigrees are well filled and the pedigree of the youngest animals can be traced back through many generations. In such situations, one common base population can reasonably be assumed. Sometimes horse populations are either: mixtures from many base populations (e.g., synthetic breeds), or there is importation of breeding stock from other countries or populations, or there are many animals with incomplete pedigrees. In such cases, an appropriate genetic grouping by creating several base populations becomes essential [26].

The AM-BLUP method has been applied for genetic evaluations in many horse breeds throughout the world. Most applications have been within Europe, where AM-BLUP methods are routinely used for genetic evaluations in riding horses, trotters, Icelandic horses, and Thoroughbreds in many countries. In some breeds, the method has been in practical application for up to more than 2 decades. The published index values for the most important traits of the breeding goals have been widely used by breeding organizations, and by individual breeders, for facilitating their selection decisions. In many cases, the breeders have access to Web applications where BLUP indices can be searched and listed in various ways. These have become valuable tools for the breeders and a large help in their mating plans. Analysis of genetic trends in these populations have invariably shown that the rate of genetic progress have been boosted by the introduction of the AM-BLUP method.

As an alternative to the BLUP method, Ricard [13] has developed a nonlinear approximate Bayesian animal model method for genetic evaluation of horses based on ranks in competitions. The method provides estimated breeding values for an underlying normally distributed liability variable from the likelihood of ranking according to some phenotypic observations in any single race or competition event. The estimated breeding values are obtained as the mean (or mode) of the marginal joint posterior density of the combined prior information and the likelihood function according to Bayesian principles. A statistical inference drawn from the resulting EBVs can be given by probability statements in Bayesian fashion. The method adjusts the likelihood for systematic environmental effects and utilizes additive genetic relationship between animals in the same way as the AM-BLUP method does. The method has only been applied for genetic evaluation of trotters and riding horses in France [27, 28]. The method is computationally demanding and general software for the method is not yet readily available. Developments of the concept of ranks (Thurstonian model) into full Bayesian analyses using MCMC Gibbs sampler methods have recently been proposed [29, 30]. The development of this methodology and modeling will continue and seems to have great potential in horse breeding.

Genetic evaluations of horses are often biased due to censoring of records [31, 32]. Horses are frequently preselected before they enter races, riding competitions, or field testing events. Information on the preselection criterion is usually lacking. However, in horse populations pedigree information is generally available on all horses, even on those without records. Therefore, the trait racing-status or test-status can be defined as an all-or-non trait, with the value one for tested animals and zero for culled or non-tested horses. Test-status has been confirmed a highly heritable trait in several horse populations (e.g., [32–34]). Environmental correlations between test-status and the recorded traits are not estimable because all animals with test-status equal to zero lack phenotypic records on the tested traits. However, genetic correlations between test-status and the recorded traits can be estimated if environmental covariances are constrained to some predefined values (e.g., zero). Indications of moderate to high genetic correlations between test-status and

performance traits in horses have been confirmed in some populations [32, 33]. Inclusion of test-status in a multiple trait AM-BLUP framework was shown to increase the accuracy of selection and increase the rate of genetic progress in Swedish trotters, where the procedure has been routinely applied for a long time [33]. Ignorance of the problem with censoring of records results undoubtedly in bias in genetic evaluations and substantial loss of genetic progress in many horse populations.

International Genetic Evaluations

Breeding of sport horses has become a big global industry. Many breeding organizations of Warmblood riding horses in Europe have implemented modern methods for genetic evaluation of breeding horses on a national scale. The increased international trade with valuable breeding horses has led to important exchange of genetic material across populations having similar breeding goals.

The Interstallion project (<http://www.interstallion.org>) was established in 1998 to harmonize and improve exchange of information between Warmblood breeding organizations within Europe. The main aims have been to: (a) describe breeding objectives, test procedures, and genetic evaluation methods, (b) recommend improvements of national genetic evaluation systems, and (c) study methods of comparing genetic evaluations across countries. The project has resulted in several publications on these subjects [35–40].

Genetic evaluations for the global population of the Icelandic horse are computed regularly and published on the Internet (<http://www.worldfengur.com>) [41].

Selection and Genetic Progress

Factors Affecting Genetic Progress

The rate of genetic improvement by genetic selection in horse populations depends on:

1. Additive genetic variability in the selected traits (σ_A)
2. Intensity of selection (i)
3. Accuracy of selection (correlation between the true and the estimated breeding value, R_{TI})
4. Generation interval (L)
5. Inbreeding depression (d)

The genetic improvement per year can be expressed as

$$\Delta G/\text{year} = \sigma_A i R_{TI}/L - \Delta d$$

Increased intensity and accuracy of selection will increase the rate of genetic improvement if it is not leading to longer generation intervals nor increased homozygosity in loci affecting the traits and the general vigor (inbreeding depression). Generation intervals are generally very long in horse breeding (8–12 years). Shortening of the generation interval often means reduction in the accuracy in genetic evaluations (R_{TI}) but the selection intensity is usually affected in positive direction. The selection intensity, generation interval, and accuracy of selection are often different for stallions and mares. Therefore, the formula above is often modified to include two or four paths [42].

Multistage Selection in Horses

In horse breeding, large increase in the rate of response to selection can often be gained by an effective scheme for genetic evaluation of young horses that is based on pedigree information and early performance testing [43, 44]. The selection of stallions and usage for breeding is usually of a multistage nature as they are selected repeatedly within the same generation [45]. The first step in stallion selection is based on pedigree information (ancestry and collateral relatives) and determines which colts get performance tested and thus undergo the second and the most important selection step for traits having medium to high heritability. Selection intensity should be high at the second selection stage, but unfortunately testing capacity is often limited, especially for riding horses. The cost and labor of keeping stallions instead of geldings is usually high and many colts are castrated at a young age before they can express their abilities. The third and final selection step is based on EBVs when the offspring results provide the main source of information. The value of the progeny information increases for traits with low heritability.

Effect of Selection on Effective Population Size and Inbreeding

Several generations of constant directional selection, in large populations with moderate selection intensity, will lead to a measurable reduction (10–30%) in the

genetic variability (σ_A), which thereafter is assumed to stay reasonably constant due to an equilibrium between the reduction in genetic variance and the variation rebuilt by recombination [46]. Therefore, in large populations with negligible inbreeding, selection is expected to be effective for changing the population mean in the desired direction over many generations.

Intense selection in closed populations (no migration) will build up increased relationship among the future members of the population. That corresponds to reduction in the effective population size (N_e) and leads to mating of related individuals, which is defined as inbreeding. Small N_e and consequently heavy inbreeding results in random change in gene frequencies across generations and a general reduction in the Mendelian sampling variance term and thus decreased genetic variability (σ_A). Accumulation of inbreeding (Δd) in small closed populations will reduce the scope for genetic improvement in the selected traits. In addition, increased homozygosity in many loci in the population will presumably affect fitness traits negatively (fertility, health, vigor, etc.) and increase frequency of genetic diseases in the population [10].

Many horse populations are at risk of getting small effective population size, due to small actual population size, intensive selection on EBVs alone, and large variation in family size. In such populations, the risk of reduced genetic variability and inbreeding depression should not be ignored and the breeding schemes should aim at sustainable long-term progress, where breeding animals are to be selected in an optimum way such that genetic improvement in the breeding goal traits and effects on future inbreeding are simultaneously considered [47–49]. Sustainable breeding plans aiming at maintenance of genetic variation should direct the selection such that future inbreeding is avoided at the cost of some loss in short-term genetic progress.

Obtainable and Observed Genetic Progress in Horse Populations

The rate of genetic response in large horse populations depends mainly on how accurately the traits reflecting the breeding goal can be measured (heritability), the amount of variation in the aggregate genotypes (genetic variability), the quality of the method used

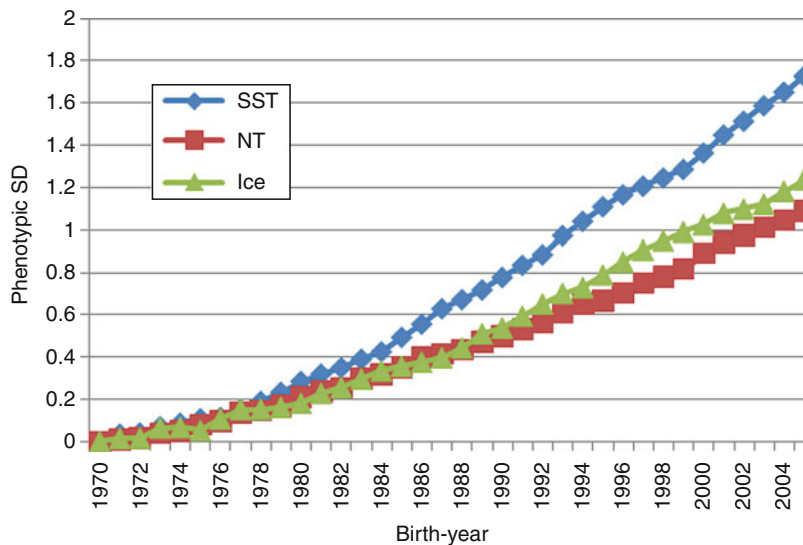
for genetic evaluation (accuracy of selection), the testing capacity (selection intensity), and the age when the trait comes to an expression and can be measured (generation interval) [10].

In horse populations with onset of testing or racing performance at 3–6 years of age, and a conventional breeding scheme, the generation intervals are normally about 8–10 years for males and 10–12 years for the females. The selection intensity could correspond to ca 5% (1–10%) for males and ca 60% (40–80%) for females. When the selection criteria are EBVs that are obtained from the AM-BLUP method, then the source of information is a combination of pedigree, own performance, and offspring results. The average accuracy of selection on the male side (R_{TI}) could be about 0.8 for trait with $h^2 = 0.2$ and about 0.9 for trait with $h^2 = 0.4$. Higher accuracy would normally require more emphasis on progeny performance, which would prolong the generation interval. The accuracy of selection on the female side depends heavily on how large proportion of mares is tested for their own performance. A reasonable assumption could be $R_{TI} = 0.45$ for trait with $h^2 = 0.2$ and $R_{TI} = 0.63$ for $h^2 = 0.4$.

Given the assumptions above, the annual genetic progress in horse populations could correspond to

4–4.5% of the phenotypic standard deviation for traits (or combination of traits) with $h^2 = 0.2$ and to 6.5–7.5% for traits with the higher heritability of $h^2 = 0.4$. For readers interested in evaluation of different combinations of factors affecting the genetic progress in large populations, where inbreeding is ignored, a Java applet is available free at the following link: www.ihbc.se/web/contents/ihbcWebApplets/GenResponseApplet.html.

Estimates of genetic trend have been reported in several horse populations. The estimated annual genetic gain has been ranging from zero up to 6% of the phenotypic standard deviation of selected traits. Estimates of genetic trend in three different horse populations may serve as examples (Fig. 1). The Swedish Standardbred Trotter (SST) is a synthetic breed originating from imported American Standardbred Trotters and French Trotters. About 5,000 foals are born annually in the SST breed. The Nordic Trotter (NT) is a heavier type (cold-blood) originating from Norway and northern part of Sweden. About 1,300 Nordic Trotter foals are born annually (850 in Norway, 450 in Sweden). The Icelandic Horse is a closed population of small, compact, and strong horses that has been purebred in Iceland for more than thousand years. It is the only horse breed in Iceland where about 7,000



Breeding in Horses. Figure 1

Realized progress in the aggregate genotype, expressed in phenotypic standard deviation (σ_p) units, in three horse populations (SST Swedish Standardbred Trotter, NT Nordic Trotter, Ice Icelandic horse)

foals are born annually. Both the trotter breeds are used for harness racing and the breeding goal consists of several traits expressing racing performance ability and sustainability. The Icelandic Horse is used for riding and is known for its gaiting abilities, willingness, good character, and hardiness. The breeding goal for the Icelandic Horse consists of a linear function of 16 traits (8 conformation traits and 8 traits measuring riding ability [gaits and temperament]). The traits are registered at special field tests.

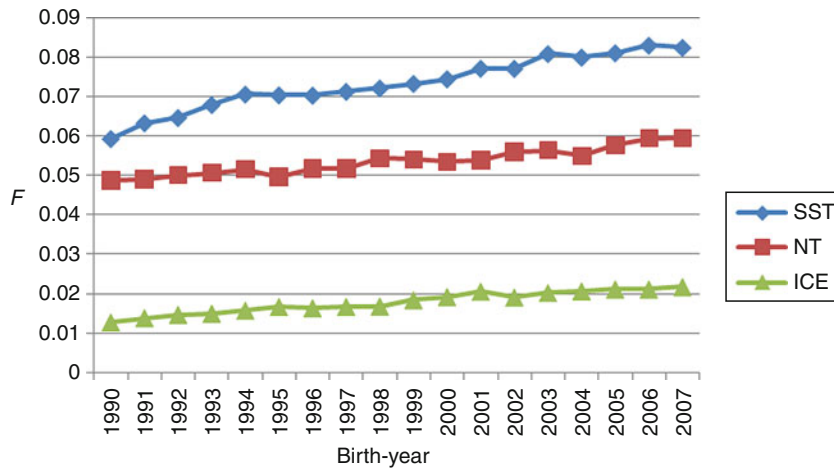
Genetic evaluations based on BLUP methods have been available as a guide for selection in these three breeds since mid-1980s. Between 1970 and 2005, the mean of the aggregate genotype (weighted mean of EBVs for several racing variables) in the SST population has been raised by $1.73 \sigma_P$ units, corresponding to the average annual $\Delta G/\text{year} = 0.049$ over the entire period. The rate of genetic gain has increased gradually over the period as seen by the increased steepness in the slope showing the trend. For the last 10 years, the rate of genetic gain has been $\Delta G/\text{year} = 0.062$, or 6.2% of the phenotypic standard deviation. In the smaller population of Nordic Trotter, the population average level has lifted $1.09 \sigma_P$ units since 1970. That corresponds to $\Delta G/\text{year} = 0.031$ over the entire period and to $\Delta G/\text{year} = 0.042$ for the last 10 years. The population mean of Icelandic horses has been raised to $1.73 \sigma_P$ units over the 35-year period or by 3.5% σ_P per year. The average rate of response over the last decade has increased by 1% of the phenotypic standard deviation, or to 4.5% σ_P per year.

In the comparison of the three breeds, the efficiency of the selection has apparently been largest in the Standardbred Trotter. This larger genetic progress can mainly be attributed to higher selection intensity, particularly on the male side, where relatively few stallions are selected on the basis of results from races where many colts compete. The high selection intensity in SST is obtained by high testing capacity (races), widespread use of artificial insemination so that each selected stallion is able to cover more mares, and excessive use of information on results and pedigree. This is clearly reflected in the larger short-term response. However, the long-term sustainability of the breeding plan in the SST breed may be questioned as explained below when considering inbreeding and effective population size.

Long-Term Genetic Progress

An important aspect of sustainable animal breeding plans aiming at long-term genetic progress is to maintain genetic diversity (i.e., variation) within the population. In closed populations, gene frequencies fluctuate randomly from one generation to another as a result of the finite sampling of gametes. This phenomenon, called genetic drift, is quantified by the term effective population size, N_e [10, 50]. In a closed population, with no migration, the N_e is dependent on the number of parents in each generation, the variance of parental family sizes and selection. One way to estimate N_e is to measure the rate of increase of inbreeding over the different generations: $1/2N_e = \Delta F = (F_t - F_{t-1})/(1 - F_{t-1})$, where F_t is the mean coefficient of inbreeding for generation t (e.g., [10]).

The development of inbreeding in the three horse populations shows different levels that have evolved since the respective base populations (Fig. 2). The figure demonstrates difference in the rate of increase of inbreeding over time across the populations and thus gives a measure of their effective population sizes. According to the rate of inbreeding and the corresponding generation intervals, the effective population size (N_e) is approximately 40 for the Swedish Standardbred Trotter (SST), 50 for the Nordic Trotter (NT), and 100 for the Icelandic horse (Ice). The rate of inbreeding per generation, ΔF , is 1.3% in SST, 1.0% in NT, and 0.5% in Ice. In guidelines from FAO [51], the minimum recommended N_e is 50 corresponding to $\Delta F = 1.0\%$ in livestock populations. Otherwise there is a great risk of loss in genetic variation, which will suppress long-term genetic progress and increase the risk for homozygosity of deleterious alleles, thus affecting health and fitness traits negatively. The SST breed is not only showing alarmingly high level of inbreeding ($F \approx 8\%$), but clearly surpassing the recommended rate of inbreeding per generation. The genetic constitution of the current generation of the SST breed is 94% of American Standardbred Trotter origin, while the remaining 6% can be traced to French Trotter base animals [33]. The American Standardbred Trotter is highly inbred with average inbreeding coefficient above 10%. The inbreeding in American Standardbred trotters and pacers is mainly due to remote inbreeding, where the horses are connected to one another by



Breeding in Horses. Figure 2

Trend and level of inbreeding coefficients (F) in three horse populations (SST Swedish Standardbred Trotter, NT Nordic Trotter, ICE Icelandic horse)

numerous paths through a small number of remote common ancestors. At the same time, breeders have deliberately avoided close consanguineous mating [52, 53]. Swedish breeders of Standardbred trotters have followed the same strategy. The average relationship among SST born in 2000 was $R = 16.4\%$ with a standard deviation of 5.2% [54]. Random mating within the population will result in average inbreeding coefficient above 8% . In order to reduce the rate of increase in inbreeding in the future, the variation in relationship among breeding candidates must be utilized in the mating strategy. Criteria for selection of breeding animals that involve EBVs modified such that the average relationship between selected animals is restricted have been proposed [47–49]. Increased migration of genetic material of French origin is also a recommended option for the breeders of Standardbred trotters in Sweden.

Breeders of the Nordic trotters have become increasingly aware of the risks associated with inbreeding in small closed populations. Negative effects of inbreeding (inbreeding depression) have been confirmed for reproductive traits, health traits, and racing performance in the Nordic trotter [55, 56]. Quotas for maximum number of mares that can be mated to each stallion have been put into effect and the rate of increase in inbreeding has reduced considerably compared with the period of 1970–1990, when the rate of inbreeding corresponded to $N_e = 32$ [57].

The inbreeding in the Icelandic horse is still at a low level and the rate of increase in the rate of inbreeding (ΔF) is yet not alarming. The breeding goal is broad as it includes very many traits, which helps keeping broad genetic variation among selected breeding individuals. However, awareness of the importance of maintaining low average genetic relationship among the selected parents is vital for the future of this breed, since import of genetic material to the closed horse population in Iceland is not a feasible option.

Genetic Progress in Racing Speed

One of the most interesting and debated questions concerning horse breeding is the “paradoxical” lack of improvement in winning times in the classical races for Thoroughbred horses over the last 50 years, in spite of significant genetic variation in racing performance variables and intense selection on racing performance [58–65].

The wild ancestors of modern horses were grazing flight animals and natural selection for speed and ability to traverse long distances were certainly important factors for the survival of the fittest. The Thoroughbred horses were founded by English and African horses screened for galloping speed and have been subject to an intense artificial selection on racing performance for over three centuries (30 horse generations). As a consequence, Thoroughbred horses are the fastest racehorses in the world galloping over distances of

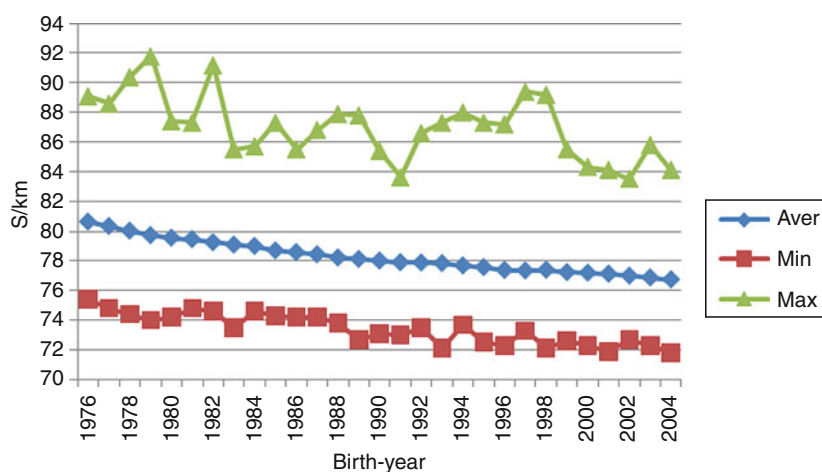
1 to 2 miles. The breeding animals have not been selected directly on racing speed or racing time. Rather they have been selected on some function of ranks in races and special weight has been put on the ability to win races. Thoroughbred horses racing in the classical races all belong to the fastest segment of horses in the population.

Gaffney and Cunningham [61] estimated genetic change in Timeform handicap ratings of Thoroughbred horses in Great Britain. They confirmed effective selection on Timeform ratings and estimated annual genetic gain corresponding to almost 5% of the phenotypic standard deviation of 3-year-old Timeform ratings. This genetic progress is not reflected in winning times of the classic races, but the authors concluded that correlated genetic improvement in speed had been achieved in the Thoroughbred population as a whole but the fastest individuals in the population had reached the physiological limits for racing speed over the distance of the classic races. This conclusion assumes asymmetry in the distribution of racing speed.

The genetic evaluations of the Swedish Standardbred Trotter involve several variables that are functions of ranks in races (earnings, order at finish in the race) and racing time. As ranks in races are measures of racing performance that are relative to contemporaries racing at the same time, a genetic progress in these variables cannot be projected to any observable

scale with clear physical meaning. On the other hand, the genetic progress in racing performance should be reflected in faster racing times. The best average racing time over 1 km has indeed improved continuously for the Swedish Standardbred Trotter since recording started for the horses born in 1976 (Fig. 3). The limits for racing speed in trotters have apparently not been reached yet. However on the observed untransformed scale (s/km), the rate of improvement has slightly reduced over time and it seems increasingly harder to break the records. The dispersion of the slowest and fastest racing time records in the population around the average is also apparently asymmetrical. Arnason [66, 67] has previously argued that genetic evaluation of racing time records should be based on scaled logarithmic transformation of racing time records as $y_i^* = \ln(y_i - x)$, where y_i is the observed racing time record on the i th horse in s/km units, x is the asymptotic physiological limits for trotting racing speed in s/km in races over the traditional distance of 1 mile. When x is equal to 68.2 the distribution of y_i^* is almost perfectly normal in the population of Swedish Standardbred male trotters and the trend in average log transformed racing time records is linear.

The trend in statistics (mean, minimum (fastest), maximum (slowest)) of fastest racing time records of 3–5-year-old males in the population of Swedish Standardbred Trotter can be described with the



Breeding in Horses. Figure 3

Observed trend in best average racing time records as 3–5-year-olds over 1 km for the average (aver), fastest (min), and slowest (max) Standardbred male trotters born in Sweden

expression: $s/\text{km} = x(1 + e^{-pt})$, where x is the ultimate asymptotic limit for the fastest racing time records in the population as defined above, p is a positive constant, and $t = \text{birth-year} - z$, where z is a time scaling constant [67]. The constants p and z were estimated from recent data on racing results in the population of SST leading to the following equations for prediction of the development of the trend in the average, fastest, and slowest racing times in the population:

$$s/\text{km}_{(\text{aver})} = 68.2 \left(1 + e^{(-0.013(\text{birth-year}-1843))} \right)$$

$$s/\text{km}_{(\text{min})} = 68.2 \left(1 + e^{(-0.021(\text{birth-year}-1867))} \right)$$

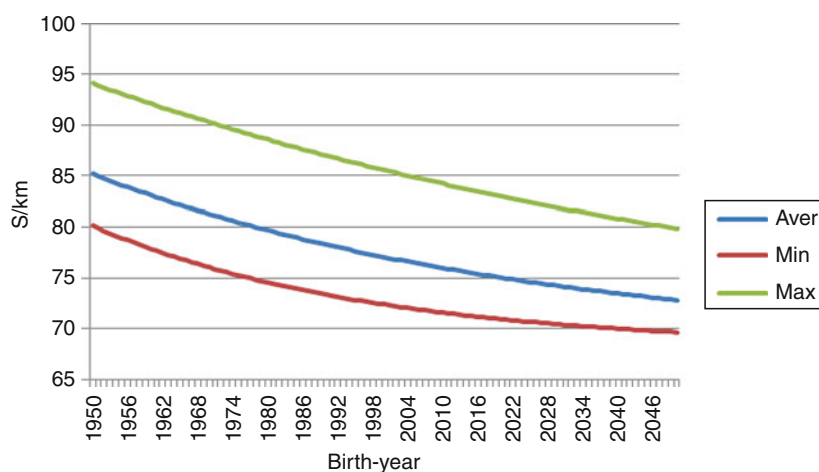
$$s/\text{km}_{(\text{max})} = 68.2 \left(1 + e^{(-0.008(\text{birth-year}-1829))} \right)$$

The predicted trend is revealed in Fig. 4. The racing time records in the population are expected to improve (become faster) at a linear rate on the logarithmic transformed scale, but at a diminishing rate on the untransformed linear scale of racing time (s/km). The presented racing times refer to “volt start,” which is the most common starting procedure for trotting races in Sweden. Records from the flying “auto start” are adjusted by adding 2 s to the racing time.

The history of selection for trotting racing performance in Standardbred trotters is much shorter than that of selection for gallop racing performance in Thoroughbreds, and probably reflects a difference of at least

20 generations. If genetic variation can be maintained in the trotter population and the selection for trotting racing performance will be continued in the same manner over the next 200 years, the prediction equations above give the following estimates: Average racing time record for males born 2210 = 68.78 s/km; fastest racing time = 68.25 s/km; and slowest racing time = 71.44 s/km. This can be compared with the corresponding observed average, minimum, and maximum racing times of males born 2004 in the SST population: 76.74, 71.8, and 84.1 s/km. A parallel between this expected scenery for the development of racing speed in trotters and that already observed in Thoroughbreds is highly tempting. The average records (and the slowest) will continue to improve, however at ever decreasing rate, far after an apparent stagnation in the improvement of the fastest records. A slight improvement of the best records will be increasingly harder to identify due to the inappropriate scale. The small difference in racing speed between the fastest horses becomes less important as relative to fighting spirit and the mental and physical ability of the horse to react to the signals of the driver (or jockey) and to variations in speed at different phases of the race.

If there are some asymptotic limits to racing speed, they must relate to a nonlinear accumulation of biological and physical constraints on racing performance. Such factors might be: energy supply, energy



Breeding in Horses. Figure 4

Predicted trend in best average racing time records as 3–5-year-olds over 1 km for the average (aver), fastest (min), and slowest (max) Standardbred male trotters born in Sweden

transport rate, neural functions, oxygen supply, oxidative enzyme activity, accumulation of lactic acid in the blood, exponential increase in energy requirement for overcoming air resistance, and generally a nonlinear risk of stress on the locomotion (tendons, bones and ligaments), respiratory and cardiovascular systems, with increasing racing speed [13, 68].

Hypothetically, an insertion of a gene with positive effect on racing performance on an inferior racing horse would be likely to have more marked effect on its racing performance than if the same gene was inserted into an outstanding racer, which would already carry many genes with positive effects on racing performance. Such scale effects can often be removed by appropriate transformation and traditional quantitative genetic analysis methods may apply. Alternatively, a nonlinear polynomial genetic model for finite number of independent loci (geometric progression) might be attempted [66, 67]. The geometric progression model assumes constantly diminishing marginal substitution effects of the alleles affecting the trait.

In conclusion, the fact that racing times in classic Thoroughbred races have not improved markedly in more than a half century in spite of available genetic variation and selection is not necessarily a “paradox.” It could merely be a result of the use of improper scale for measuring racing times in horses approaching their biological limits.

Future Directions

Methods of organized animal breeding using BLUP animal models and selection on EBV for important traits have proved useful in many horse populations worldwide. Genetic progress at the annual rate of 3–6% of the phenotypic standard deviation has been reported in several populations. Sustainable breeding schemes yielding this rate of constant response over a long period and at the same time maintaining sufficient genetic variability in the population can be accomplished with established knowledge and relatively cheap technical equipments.

In many parts of the world are rational and organized breeding plans still lacking in large and locally important horse breeds. In some societies, this can be explained by poverty and lack of higher level of education. In others is the social culture, including reluctant

conservatism, a hindrance to the introduction of new technique and scientific influence on the traditional horsemanship and “horse culture.” This will certainly change and introduction of new and modern organized breeding plans for horses will undoubtedly be seen in many countries in near future.

The increased international trade with valuable breeding horses and exchange of genetic material across horse populations has created need for international genetic evaluations, where EBVs can be fairly compared across countries. The need for international genetic evaluations will certainly grow in the near future.

Methodological developments in genetic evaluation procedures and statistical models will undoubtedly enhance future breeding in horses. Of particular foreseen interest is genetic evaluation of ranks in competitions based on Bayesian Thurstonian models [29, 30] and use of random regression models for evaluation of traits with repeated measurements [20, 21].

Recently, the horse genome has been fully sequenced and the results are available to the scientific community [69, 70]. This has created optimism that genomic selection, which is selection on genomic breeding values (GEBVs), might revolutionize future horse breeding. The GEBV are calculated as the sum of the effects of dense genetic markers across the entire genome on the trait of interest. The genetic (DNA) markers are in the form of a large collection of chromosome fragments, so-called SNP (single nucleotide polymorphism) chips. Since GEBV can be obtained already in young foals, the possibility to shorten the long generation intervals in traditional horse breeding and to hinder castration of genetically valuable individuals is obvious. Genomic selection has the most potential for genetic improvement of traits that are manifested late in life and of traits with low heritability. Breeding for performance traits in sport horses, longevity, and various health traits in horses could benefit enormously if genomic selection can be practiced in a cost-effective way.

More methodological as well as technical development is required before genomic selection can gain widespread practical application in horse breeding. The first step is the development of a sufficient number of high-density SNPs across the entire horse genome and the second step is to genotype large reference populations in different horse breeds with phenotypic

records so that the effects of the markers on the phenotypes can be analyzed. In subsequent generations, a large number of horses will need to be genotyped for the markers to determine which chromosome segments they carry. Then the estimated effects of the segments can be summed across the whole genome to predict the GEBV [71]. This new technology is already revolutionizing dairy cattle breeding in several countries [72, 73] and an efficient algorithm for computing the relationship matrix by use of genomic information has been invented [74]. A combination of a traditional selection on EBVs and a selection on GEBVs is likely to be adapted soon in the most valuable sport and racing populations, where the cost of genotyping is little in relation to the value of the breeding animals and organized breeding plans with registration of data on phenotypes and pedigrees are already in function. As a dramatic reduction in the cost of genotyping can be anticipated in the future, a practical and widespread use of genomic selection may become reality in breeding of horses throughout the world sooner than expected in the light of current status and prizes. An important challenge will be to meet unforeseeable snags that may rise from the use of the new technique and difficulties in managing future genetic variation and long-term genetic gain.

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Bus Rapid Transit and Light Rail Transit Systems: State of Discussion

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Article Outline

Glossary
 Definition of the Subject and Its Importance
 Introduction
 BRT Developments
 Light Rail Developments
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Glossary

Bus rapid transit (BRT) An integrated bus-oriented public transport service composed of six basic elements: higher-quality, more styled buses; a well-designed service plan, including route structure is faster and more frequent transit service than typically experienced with regular route local bus service; upgraded, appealing passenger stations; roadway infrastructure that gives BRT priority in mixed traffic or separated from other traffic entirely to help ensure faster travel times; intelligent transportation technologies, not only for traffic priority as mentioned above but also for real-time passenger information and vehicle tracking to ensure more ambitious service schedule; and clear, distinct branding and marketing [1].

Bus rapid transit vehicle A bus used in BRT service, typically with advanced features such as

aerodynamic styling, hybrid electric drive or other advanced propulsion, and real-time tracking systems, similar to what are now used in rail transit systems.

Buy America Provisions of federal transit law that govern purchases of goods with federal surface transportation assistance grants. Certain aspects of this policy date back to protectionist sentiments of the 1930s. In 1978, Congress stipulated that for purchases of rolling stock, these would be considered to be US made if they were assembled with at least 60% of components and materials by value supplied by US sources. The rules have been subsequently refined and subject to controversy several times since [3].

Capital assistance/expenditures Government subsidies for expenses related to the purchase of equipment and facilities, such as stations, buses, and trains; maintenance facilities; and support systems. Such equipment typically means property that has a useful life of more than 1 year. Capital expenses do not include operating expenses that are eligible to use capital funds.

Commuter rail service Regional-distance, usually locomotive-hauled passenger train service often sharing tracks with freight railroads. Chicago's Metra service is an example.

Federal Transit Administration A sub-cabinet-level government agency of the US Department of Transportation that administers a variety of grant programs that help fund bus and rail transit projects in US cities, Puerto Rico, and the US territories, as well as rural areas and federal lands.

Fixed-route bus service Traditional form of transit bus service, typically with frequent stops along a defined route. The bus services of the Chicago Transit Authority are an example.

Light rail transit (LRT) A form of urban rail public transportation that generally has a lower capacity and lower speed than metro (also known as heavy rail) systems, but higher capacity and higher speed than traditional streetcar systems. These rail systems are typically electrically powered, usually by overhead catenary. They ideally operate their own rights-of-way separated from other traffic but if necessary can also operate in mixed traffic on city streets [2].

Modal split Term of art in public transportation for market share. That is, the percentage of journeys taken with the various forms of public transportation, as compared with walking, bicycling, or the private automobile.

Operating assistance/expenditures Government subsidies for expenses associated with the operation of the transit agency and its passenger services, including vehicle operations (e.g., bus, train, "dial-a-ride," and vanpool services), vehicle and facility maintenance, and general administration (e.g., marketing, top management, insurance, and finance). Operating expenses also include salaries, wages, and benefits as well as outsourced services under contract.

Privatization In its strictest definition, it is the return of publicly owned and operated public transport services to the private sector. However, in the USA, it is also defined as the contracting of publicly owned services to private companies, private participation in the capitalization or ownership of these publicly owned services, or the franchising of these services to private firms.

Public transport service Bus and rail services operated either by public or private organizations on a scheduled or on-demand basis. These services are distinct from charters, which are hired for groups such as tours.

Public-private partnerships/models Synonymous with most definitions of privatization except the complete return of transit services to private ownership and operation with minimal oversight.

Purchased transportation services Bus and train service provided by others through a contract; also called contract service.

Rolling stock Industry term for buses and trains and other vehicles used in public transport service.

Transit-oriented development Land use patterns such as higher densities around BRT and rail stations that also contribute to greater transit usage on these systems.

Transportation Equity Act for the 21st Century Also known as TEA 21, the landmark surface transportation assistance law passed in 1998 that ended operating assistance for agencies that served urbanized regions with fewer than 200,000 residents. It also for the first time guaranteed a stream of funding for capital assistance over the 6-year period

in which the law was effective, which helped public transportation agencies better manage and plan their capital expenditures.

Travel time savings Industry term for the average estimated savings per trip on new transit systems as compared with the average travel time from a commute taken by an automobile or by the previous bus network serving the route.

Urban Mass Transportation Act The 1964 federal law that began the federal government's involvement in the oversight and financial assistance of regional, state, and local public transport services.

Vehicle maintenance Activities associated with bus, railcar, and support vehicle (e.g., fueling and repair trucks) maintenance (repairs and routine replacement of parts) and servicing (cleaning, fueling, etc.), also including inspection and oversight of these activities. In addition, vehicle maintenance includes repairs due to vandalism and accidents.

Vehicle operations Those activities associated with providing scheduled and on-demand passenger services, such as vehicle dispatching and scheduling, driver and technician training, ticketing and fare collection management, and system security.

Definition of the Subject and Its Importance

Increasingly, light rail transit (LRT) and bus rapid transit (BRT) are the two solutions cities throughout the world most often turn to in a broad variety of urban public transport applications to address a wide range of mobility challenges. While regional rail schemes (also called commuter rail in the USA and Canada) are also experiencing rapid growth, and many cities that have metros (also known as heavy rail in the USA and Canada) continue to expand their networks, LRT and BRT are even faster growing modes.

Whether LRT, BRT, metros, or commuter railroads, virtually all large cities in the developed world now boast at the very least starter urban passenger rail systems, in many instances restoring only partly the networks these cities had a century or more ago. Many of these have since supplemented the initial segments with a second wave of lines to build out their networks. Meanwhile, a growing number of midsize cities in the developed world, including a rapidly growing list of cities in developing countries, have also

added networks. Call these stages the first two waves of the worldwide public transport renaissance. Now public transport infrastructure investment is entering a third wave of the renaissance, in which the growth of public transport investment becomes an essential and integral part of a nation's or a region's balanced transport strategy.

BRT is perhaps the fastest growing public transport mode in a century. Only 12 years ago, 17 US cities were selected by the then Federal Transit Administrator Gordon Linton to participate in his BRT Consortium. Just 5 years later, according to congressional sources, more than 50 and as many as 75 communities have a BRT project in some stage of development. Today, virtually every project seeking federal financial support, regardless of mode, also studies a BRT alternative, thus putting the mode on equal policy consideration with other public transport strategies.

The simplest and most often used definition of BRT is a public transport concept that "thinks like rail but uses buses." The interest in it is borne out of desire to offer increasingly congested cities a flexible, relatively inexpensive alternative to more highways or more expensive and longer-to-implement transit alternatives. Applications range from feeder systems to rail lines (e.g., Los Angeles) to downtown circulators (e.g., Orlando and Denver) to urban transport spines in their own right that can change the region's modal split and stimulate transit-oriented investment (e.g., Bogotá, Curitiba and Eugene, Oregon).

Similarly, applications of LRT range from spines for smaller cities that cannot justify the expense of metro systems to feeder systems to metros or regional passenger railways to circulators that often run in the street with other traffic. These last systems are often called trams or streetcars, as well. The flexibility of LRT also results in systems that operate in their own rights-of-way either underground, in elevated structures or at grade, as well as combinations of all of the above.

Since 1975, 23 cities in North America alone have fueled the rebirth of LRT development. Prior to that year, only seven cities had such services, as most were discontinued in favor of road and highway investments. LRT services now operate in 24 US cities, as well as three each in Canada and Mexico. Still more are under construction or in various other stages of development [4].

Introduction

BRT and LRT systems are being planned, constructed, and opened for service at a faster pace than previously, because these projects today tend to be smaller projects than metros, and as such are better suited for smaller applications, such as network spines for small cities, lines for suburb-to-suburb commutes – long the overwhelming share of journeys to work in the USA and a growing trend elsewhere as well – and for smaller-scale feeders to previously established systems.

In addition, these systems, particularly smaller, often street-running LRT lines known as trams or streetcars, but also BRT in a growing number of instances as well, serve as outstanding reshapers of the built environment and as economic catalysts.

They also help provide solutions to another worldwide trend: the aging of the population in the developed world. It has already taken hold in Japan, Europe, and Canada, and is becoming an increasing challenge of the USA. Older persons generally prefer to drive less, and they require smaller homes. Many also prefer to live nearer to better health-care services, nearer educational, cultural, and arts institutions, and otherwise “where the action is,” or where their extended families are – that is, in cities.

This third wave is also driven by other powerful demographic forces. These include the population growth worldwide, as well as the concentration of that population in cities. This urbanization includes not simply the teeming populations of the developing nations, but also in the USA and other developed economies.

As a consequence, this current wave of public transport investment could be the largest expansion yet. However, as will be explained below, this third wave will require a different approach to project development and management.

BRT Developments

There are two major reasons why BRT has been so attractive to city planners. First, BRT projects are typically a fourth of the cost of comparable light rail projects. In addition, BRT can be implemented in roughly a third of the time – or even less – to design and build [5].

For example, the Los Angeles County Metropolitan Transportation Authority (MTA) built and opened its Orange Line BRT in the West San Fernando Valley to light rail standards (to enable a future conversion if it so chose) for \$330 million; it took 3 years to design and construct, even with court-ordered stoppages to address neighborhood lawsuits that were concerned about noise, as well as delays caused by construction interruptions from one of the rainiest winters on record in the region. A roughly comparable LRT line in the service area, the Gold Line, took more than a decade to develop and opened at a cost of approximately \$1 billion. Moreover, the Orange Line carries more weekday passengers than the Gold Line [6].

According to the US Senate’s Banking Committee staff analyses, more than 50 American communities are developing BRT projects; that number grew with the addition of roughly 2 dozen BRT earmarks in SAFETEA-LU. The accompanying table provides a list of these projects.

Based on a BRT market study performed for the FTA in fall 2002 and updated in 2007 by the advanced transportation research consortium WestStart – CALSTART (Pasadena, CA), as many as five new BRT systems per year and/or ten new BRT corridors could open each year between 2007 and 2010 [7].

Interest in BRT outside the USA is even stronger. Based on success of the TransMilenio, which carries nearly two million boardings per weekday in Bogotá, the government of Colombia has launched a new policy to develop BRT in six other cities. Nearby Ecuador is also planning BRT lines in at least three of its cities. Cities in Peru and Chile are also planning systems.

These successes in many ways emulate the achievements of Curitiba, Brazil, which many point to where BRT began. Despite having the second highest automobile ownership rates in Brazil (only after the country’s capital, Brasilia), approximately 70% of weekday journeys are on public transport, mostly on the city’s BRT network.

In Asia, Beijing is in the throes of building a six-line network, which began as part of its preparations for the 2008 Summer Olympics; as many as a hundred more cities in China are studying networks, as the government there has included BRT as a transport solution for corridor applications whose volumes warrant less than a tram or light rail investment. The Korean Ministry of

Transport is not only involved in assisting several cities in network planning and construction, it is working with a manufacturing consortium to design and commercialize a next-generation BRT vehicle.

Several African cities view BRT as a cost-effective mobility solution in their plans to cope with rapid population growth, most of which is urbanization. Accra, Ghana as well as Johannesburg and Cape Town in South Africa have opened new systems (the latter two in preparation for hosting the FIFA World Cup this past summer).

India's Ministry of Urban Development has issued a new report, "National Urban Transport Policy," which encourages its lower-density cities to develop BRT. Accordingly, the ministry has approved BRT projects in Ahmedabad, Indore, Jaipur, and Pune.

Like South America, Europe and Australia were at the forefront of BRT and continue to witness new projects. In the UK, projects are part of Quality Bus Corridor projects, many of which featuring guided bus systems, including two in Leeds, and one each in Edinburgh, Ipswich, and Bradford. The next to open will be the world's longest guided busway, the 26-km Cambridgeshire Guided Busway built on an abandoned railway right-of-way between Cambridge and St. Ives. Manchester and Luton have also schemes in development.

The industry publication METRO has been tracking the growth of BRT in its annual "BRT 25" survey. Its most recent survey [8] found that the average project cost for BRT networks under development is \$143.8 million for new projects.

Light Rail Developments

Though not as fast as BRT in recent years, growth in LRT systems around the world has also been impressive. In the USA, only 11 cities operated modern LRT or their historic counterparts, streetcar services. Today, more than 30 do, and many of those have opened additional lines to build out their networks [9].

In other North American and South American countries, the growth rate has not been as high as in the USA, but most either continue to operate the networks they started or have expanded them. In Mexico, LRT is available in Guadalajara, Monterrey, and Mexico City. In Canada, five cities operate such systems,

including Toronto, Edmonton, Calgary, Ottawa, and Vancouver. A sixth, Waterloo, Ontario, is planning such a system.

A recent phenomenon has been the growth in planning, constructing, and opening streetcar lines (also called trams in Europe and some parts of Asia). Interest in streetcars represents a return to an old idea, mainly because of their history in attracting and focusing strong economic development adjacent to their lines. Indeed, the Smithsonian Institution's recent exhibit on public transport history explained that interurban streetcar lines were built throughout the USA to connect new real estate developments [10]. Henry Huntington became rich not just because of his Pacific Electric rail empire in Southern California but also because of similar, though smaller, enterprises in other parts of the nation [11].

Today's applications comprise either modern technology, such as the systems recently opened in Portland, Oregon, Seattle and Tacoma, Washington, and Nottingham, England, or the one opened in the early 1990s in Strasbourg, France; or heritage (or vintage) systems, such as the one in Kenosha, WI. However, most streetcar lines in the USA and elsewhere in the world employ modern vehicles and other technologies.

Interest in these two modes in recent years has been more intense than that surrounding light rail in the late 1970s and early 1980s and commuter rail in the 1990s, the last emerging markets in public transport. In fact, BRT and streetcars very likely will exceed the other US rapid transit markets not only in project cost but also in the number of projects, even at a time when these other public transport modes are also growing robustly.

In most of the developing nations, BRT will likely be the favored mode, while in many European nations light rail-based systems will be favored. Rail will also continue to be preferred in more densely populated cities of Japan, Korea, and China, though in these countries the mode of choice will just as likely be metro systems as LRT, particularly for the "backbone" lines of networks. However, BRT and tram systems will increasingly become surface network supplements even in these cities, creating stronger networks than benefit all modes of public transport – what telecoms and IT experts call "network effects."

This trend will continue if not accelerate for four fundamental reasons. First, throughout the world, there is a growing recognition that greater investment in public transport improvements is needed to cope with worsening congestion and increasing urbanization throughout the world. Shanghai, Bangkok, Abidjan, Sao Paulo, Mexico City, Cairo, and even Paris and London face ever-increasing metropolitan growth and its attendant problems. Indeed, a recent study found that every other person on the globe lives in a city and that by 2030 60% of the population will live in cities, 23 of them with more than 10 million in population [12]. Only a handful could be characterized as high density.

Second, BRT and streetcars are now considered legitimate tools in urban transport planners' toolkit. Third, BRT, but particularly rail-based public transport modes, are increasingly viewed as good catalysts for economic development, which can also attract private capital to build and operate these systems. Finally, growing fiscal pressures make smaller-scale and faster-to-implement projects more viable relative to more expensive and longer-to-deploy alternatives.

Each of these modes shares some characteristics, but each also has strengths and weaknesses relative to the other modes. For example, BRT is more flexible and typically faster-to-implement, more scalable, and less risky from a project management perspective. On the other hand, streetcars can attract private capital more easily, because their return on investment tends to be much higher – as much as 2–3 times higher – than BRT.

Current and Future Trends

Both rail-based and road-based public transport investments present a much different set of opportunities for policy-makers and thus will continue to require different strategies. These are briefly summarized below and elaborated upon later:

First, BRT and LRT projects in the future will tend to be smaller but many more will be developed. Each project will be smaller than the transit projects in the past, but there will be many more such investments than traditional, larger rail projects, even though all public transportation investments continue to grow rapidly. Implementation and management of these requires a more nimble and flexible oversight, one

that is able to respond to changing conditions more quickly.

Second, such smaller systems will be implemented with much more interdisciplinary interaction not only within the project team but also with some different stakeholders. Often because they are far more likely to be built in smaller cities that have less technical expertise than their larger counterparts, BRT and streetcar systems will be implemented for project sponsors that will tend to rely more heavily on turnkey and concession-based project delivery methods, such as design-build, design-build-operate-maintain, and build-operate-transfer techniques to transfer project risk to private sector experts, accelerate or even help finance projects than with larger urban rail transport projects. This will require project sponsors and their contractors and other consultants, as well as city officials, professional planners, the business community, and other project stakeholders to analyze opportunities in a more interdisciplinary, collaborative approach.

Third, smaller projects will shift financing of them away from central government funding to more decentralized sources, including state, regional, and local governments and, increasingly, even private sources. The progress of this trend will depend on how each country's government is structured. In the USA, even though federal public transport assistance programs have recently been modified to better assist BRT and streetcar projects, they will likely rely less on federal support and more on state, local, or even private sources of funding, which will require different project management, outreach, government affairs, and financial planning strategies than larger projects. This is partly because the explosive growth in interest in such projects has already outstripped available funding. This resource competition combined with lower-average project costs and faster implementation for BRT and streetcars prompts many localities to bypass centralized funding and approval processes altogether.

In many countries, this is already the norm. For example, the central governments of Germany and France contribute well less than 50% of project cost. Moreover, private concessions are responsible for designing, constructing, and operating most new urban transport projects outside the USA [13].

Meanwhile, another interesting trend that has emerged has been the consideration of BRT designs

that can be converted at a future date to LRT. Although many cities have designed busways and bus rapid transit running ways that can be converted to future light rail operation, few cities have done so. Seattle's Downtown Transit Tunnel is the most recent such example.

Several cities, however, are beginning to look at BRT as an incremental step to future LRT, whether as political cover against criticism of rail advocates who see BRT as a lower quality investment or as a way to lay groundwork for an incremental strategy, when ridership and political support warranted a higher-capacity solution.

Various scenarios for designing BRT running ways to accommodate future light rail have been advocated and studied. An interesting recent experience occurred in San Francisco, where city planners there examined how its Geary Avenue Corridor BRT Project could be designed to accommodate light rail transit (LRT) at some point in the future. San Francisco County's Proposition K specifically envisioned that Geary, one of the busiest corridors in the city, accommodate a "BRT service with exclusive lanes and dedicated stations. . . designed and built to rail-ready standards." The San Francisco County Transportation Authority (SFCTA) staff concluded earlier that light rail was not financially possible within the provisions of the referendum's 30-year Expenditure Plan and thus drafted the plan in a way that required all center-running BRT design alternatives for Geary to be "rail-ready" [14].

Two center-running alignments with exclusive lanes were selected for detailed "rail-readiness" evaluation using three definitions of rail readiness. The first definition is a minimal package of design guidelines that would produce an alignment that does not preclude a future conversion to light rail; such an approach would use LRT-standard horizontal and vertical clearances, grades, adjacent tangents, and turning radii, as well as stations sited at locations that can accommodate a light rail platform (typically 180 ft vs. a typical 120 ft BRT platform).

The second definition goes well beyond this approach, to comprise a series of investments that would lead to LRT conversion much more quickly, with less incremental financial expenditure and fewer impacts to nearby businesses and transit riders. This definition includes the design criteria of the first

definition, but would also provide additional design detail for surface and subsurface infrastructure, including all trackwork (rail, fasteners, and concrete supportive slab); all electrical and communications ductbanks, manholes, catenary pole and substation foundations for traction power cables and train control wiring; ductbanks and concrete boxes for stray-current protection against corrosion; any necessary drainage work; and utilities relocation needed, including work to preserve access by these utilities so as not to interrupt BRT service. This definition considerably narrows the differences between this version of BRT and the cost and construction considerations for light rail. The third definition used in San Francisco is between these extremes in the range of investments, though closer to the first definition.

Because of budget constraints as well as the fact that light rail for this corridor was not likely in the near future or even two decades after revenue opening of BRT, the first definition of rail readiness was selected by city planners. They were concerned that even though the other definitions' additional up-front investment obviated some construction when any decision was made to convert to LRT, the remaining construction needed for LRT would still require a great deal of development time as well as create disruptions to neighborhood businesses and residences [15].

This analysis comports with the experiences of other cities seeking to design BRT running ways for a future LRT. For example, the staff of the Metropolitan Transit Authority of Harris County, Texas (known locally as Houston Metro) returned to a policy that committed to LRT for all five of its future rapid transit lines, after it initially considered "rail-ready" BRT (which was even given a new term, "guided rapid transit") on four of these five lines under development.

Houston Metro staff had repeatedly made representations to the public that the lines can be converted without disruption to service, to include the rail embedded into the corridor and all systems except for the electric traction system [16]. In the end, however, it abandoned any "rail-readiness" strategy and opted to eliminate the incremental step [17].

The difficulties of designing BRT for a future LRT are underscored by the initial design of Seattle's Downtown Transit Tunnel. It was designed to accommodate LRT at some point in the future, and even

included rails embedded in the tunnel's roadway. Other important rail transit design elements were incorporated at that time, including rail-oriented horizontal and vertical geometry requirements, tunnel clearances for LRVs, station platform lengths to accommodate four-car LRV trains, station widths, and sizing of structural elements to support LRV loads.

However, LRT technology has changed significantly since the original tunnel's design in the late 1980s, in many ways which were not anticipated when the tunnel was designed roughly two decades ago. For example, the conversion, which was completed in late summer 2007, included a new LRT traction power system (with attendant retrofit of grounding and other corrosion protection), track and platform modifications to accommodate low-floor LRVs not available in North America at the time the tunnel was designed, upgraded fire/life safety systems to comply with toughened regulations, and improved train control and communications systems to support an integrated joint bus and rail operation. Importantly, the tunnel bed was also lowered to accommodate both low-floor LRVs and buses [18].

In addition, the bus service that used the DSTT was rerouted to the surface streets of the area during tunnel reconstruction. To minimize these adverse impacts, additional police officers were assigned at key intersections who supplement the police force that was also reassigned to surface bus operations. A large public information campaign was also launched to explain the transition. The cost of these measures combined with the retrofit work exceeded \$100 million [19].

In all three scenarios of rail readiness studied in San Francisco, the most minimal "does not preclude LRT" approach would have cost \$2.8 million more than the baseline cost estimate for a two-lane BRT center-running exclusive running way, or slightly less than a 3% premium. For the second scenario, total project costs would have approached nearly 100% more than a comparable baseline center-running BRT running way cost estimate. The third scenario of rail convertibility studied for the Geary Corridor, which includes more features than the first definition but not as many as the second, would have been approximately 10% more than the baseline design [20].

Importantly, some significant costs are excluded from these comparisons, however. For example,

vehicles, commissioning and testing costs, and any necessary retrofit of maintenance facilities to accommodate future LRV designs, catenary and substation technologies are not included, because these technologies have been undergoing the most rapid evolution and are thus more difficult to project in the future [20].

Conclusion

When modern light rail systems were developed, the mode represented the avant-garde of the public transport renaissance, as a growing number of cities throughout the world planned and constructed LRT systems. That wave of the renaissance gave way to subsequent, more rapidly accelerating phases involving BRT and streetcars, as cities increasingly looked upon public transport and strategies that were central to addressing urbanization, congestion, sustainable mobility, and economic revitalization. Because those challenges will be no less daunting tomorrow, the public transport renaissance, particularly the part that includes BRT and street-running light rail, continues to be bright.

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Bus Rapid Transit, Institutional Issues Related to Implementation

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Article Outline

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Glossary

Dual-mode buses Buses that operate under both manual and partially-to-fully automated control.

Intelligent transportation systems A system or service designed to make the movement of people or goods more efficient, safer, more economical, and less polluting. Such systems work by applying advanced and emerging technologies in information processing, communications, and electronics to surface transportation needs. People can use these systems or experience their influence at home, at work, driving in his/her automobile, waiting at a bus stop, crossing a street, riding on

a bus, or looking for a parking space. Examples of ITS technologies with transit applicability either already deployed in particular settings or at least under investigation, include advanced vehicle identification systems, electronic fare payment systems, interactive trip planning systems (kiosk, personal computer), transit signal priority systems, safety and security systems, intelligent vehicle systems (e.g., collision warning systems (frontal, side, and rear), precision docking, and lane-keeping assistance systems) and operations management systems (e.g., computer-aided dispatch system, automatic vehicle location systems, automated scheduling and dispatch software, automatic passenger counter systems, and vehicle component monitoring systems).

Multimodal Involves more than one mode of transport for passengers.

Quality of service The overall measured or perceived performance of transit service from the passenger's point of view.

Stakeholders A person, group, or organization that has direct or indirect stake in an organization or enterprise because it can affect or be affected by that organization's or enterprise's actions, objectives, and policies. Key stakeholders in the implementation of a bus rapid transit system include public transit agencies and municipal or state departments of transportation.

Technology push/market pull A term customarily used in a company's business strategy for a new product or innovation that implies that a new invention is pushed through research and development (R&D), production, and sales functions onto the market without proper consideration of whether or not it satisfies a user need. On the contrary, an innovation based upon market pull has been developed by the R&D function in response to an identified market need.

Transit choice riders Riders who choose to use transit for their trip making, particularly during peak travel time periods for work-related trips, even though they have other means of travel, especially a motor vehicle, available to them. Such riders may choose transit over other modes for a variety of reasons, including saving money, avoiding driving in congested traffic, being able to use travel time

productively for other activities, and helping the environment.

Transit-oriented development (TOD) A mixed-use residential or commercial area designed to maximize access to public transport and often integrates features to encourage transit ridership.

Definition of the Subject

Bus rapid transit (BRT) is an innovative, high-capacity, lower-cost public transit travel mode that can improve urban mobility to help make bus transit more attractive by enhancing customer quality of service with an ultimate goal of increasing ridership that contributes to relieving traffic congestion. BRT systems can easily be customized to community needs and incorporate state-of-the-art, low-cost technologies as part of their flexible and incremental implementation approach.

For purposes of this entry, the following definition of bus rapid transit taken directly from [1, 2] is used:

- Bus rapid transit is a flexible, rubber-tired form of rapid transit that combines stations, vehicles, services, running ways, and intelligent transportation systems into a fully integrated system with a strong image and identity. Bus rapid transit applications are designed to be appropriate to the market they serve and their physical surroundings, and they can be incrementally implemented in a variety of environments (from rights-of-way totally dedicated to transit to streets and highways where transit is mixed with traffic).

Running ways for BRT include mixed traffic lanes, curbside bus lanes, and median busways on city streets; reserved lanes on freeways; and bus-only roadways, tunnels, and bridges. Most stations are located curbside or on the outside of bus-only roadways and arterial median busways. Similarly, BRT stations have low platforms since many are already being served or are planning to be served by low-floor buses. Conventional standard and articulated diesel or compressed natural gas buses are in wide use for BRT operations, and there is a continuing trend toward innovations in vehicle design, including environmentally clean or green vehicles; dual-mode operations in particularly appropriate settings such as tunnels; low-floor buses; more and wider doors; and use of distinctively branded bus rapid transit vehicles and stations. Service innovations

include fare-collection procedures and station design. Intelligent transportation systems range from existing and more customary automatic vehicle locations systems, transit signal priority systems, and passenger information systems to more advanced systems including intelligent vehicle systems.

Introduction

Though there has been renewed interest in its use, bus rapid transit is not a new concept. A brief discussion of the beginnings of bus rapid transit is presented in this section of the entry to provide an historical context of BRT to better appreciate from where their institutional issues derive (section “[Institutional Issues: A Broad Perspective](#)”).

The Origins of the Bus Rapid Transit Concept

As early as the 1930s in the USA, bus rapid transit was suggested in a transportation plan for Chicago, Illinois, that called for converting rail rapid transit lines to express bus operation on certain highways with on-street distribution in the central business district (CBD) [1]. In the late 1950s, transportation agencies looked for ways to implement high-quality, low-cost transit service; for example, in a 1957 study [3], California investigated high-speed bus operations for commuter travel in the San Francisco Bay Area. The proposal called for using a freeway – then under construction – for high-speed bus service utilizing what was then considered modern improvements including park-and-ride lots, pedestrian friendly designs, and improved amenities. The report acknowledged that BRT was the “most economic form of rapid transit that can be operated in this area under present conditions” [3].

Design studies for bus rapid transit within freeway medians were developed in the late 1950s in the Washington D.C. area, which recommended that “in planning of future radial freeways a cross section . . . be provided to afford maximum flexibility and reserve capacity for vehicles as well as for the mass movement of people” [1]. In 1959, the St. Louis, Missouri transportation plan included an 86-mile bus rapid transit system, of which 42 miles were to be special grade-separated bus roadways. The focus of this proposal was an elevated loop road circling downtown St. Louis [1].

In 1963, Crain [4] presented a BRT concept, calling for transportation planners to devise new transit services that replicate the high performance, door-to-door service offered by automobiles, while remaining within the economic reach of most cities. Such a system, Crain states, “combine(s) the best features of rail rapid transit and conventional bus operations by retaining the flexibility of one while obtaining some of the speed and capacity of the other” [4]. Crain also described the use of exclusive lane use and preferential traffic controls for the rapid bus concept. People-throughput capacity of such a service was also emphasized in order that this concept be effectively sold to politicians and the public [4].

Crain promoted most of the features that are being incorporated into today’s BRT systems including exclusive lanes, transit signal priority, rapid fare-collection techniques, quick boarding and alighting, and enclosed pre-boarding payment stations. His preliminary cost estimates showed BRT producing high-capacity service (10,000–20,000 passengers per hour) at a fraction of the cost of rail. His estimates also showed that BRT would cost only 2% of the cost of rail for at-grade BRT service and only 10% the cost of rail for an elevated BRT system [5]. He also discussed the importance of providing up-to-the-minute schedule information to passengers (a precursor to today’s automated vehicle location systems and passenger information systems technologies), the importance of overcoming the negative sentiments of transit (bolstering its image), and the need to properly sell the service (marketing). All of these concepts have been incorporated into what we today know as bus rapid transit.

In 1970, Milwaukee, Wisconsin, proposed a transitway plan that included 107 miles of express bus routes over the freeway system and an 8-mile, east–west transitway equipped with 39 stations (excluding downtown) and 33,000 parking spaces [6].

Dual-Mode Systems

Several additional reports from the 1960s outlined many of the same goals and operational characteristics sought in today’s BRT but envisioned an even more sophisticated system. Many of the BRT concepts that were explored during the late 1960s and early 1970s focused on providing BRT with, at least, partial system

automation. The most common concept involved the use of dual-mode buses. The idea was to combine the flexible collection and distribution capabilities of a bus system with the high line haul performance of an exclusive right-of-way rail system, all with a single seat trip and utilizing automation technologies. The most emphasized features of the systems during this period tended to be full bus automation (for a portion of the route) and exclusive right-of-way of the line haul segment. The hope was that this automation component would permit a reduction in operating costs by eliminating the need for a driver for a portion of the trip, while providing greater line haul capacity than could be achieved through manual driving alone. Meanwhile, exclusive right-of-way (busway or bus lane) would remove the vehicle from the most heavily congested portions of the trip, and permit higher operating speeds, making the transit trip more attractive. Interest in the dual-mode concept at the time declined due to (1) insufficient technological capabilities for cost-effective automation of vehicles, (2) operational savings based on the assumption that the vehicle would be “driverless” for the trip’s line haul portion was problematic, and (3) costs of grade separations envisioned for busways greatly reduced the capital-cost savings as compared to a rail system [6].

Early Busways

During the 1960s and early 1970s, bus rapid transit projects were implemented in several regions within the USA, though appeared to be diluted versions of Crain’s original concept. Most bus services that were implemented utilized exclusive bus lanes on freeways, but none really utilized a mix of multiple strategies. These projects, therefore, functioned merely as express bus services, whose effectiveness depended primarily on congestion free bus lanes to provide most of the operational improvements. The most notable projects during this period were the (1) Shirley Busway in Washington D.C. [7, 8], (2) El Monte Busway in Los Angeles, California, (3) Holland Tunnel bus lanes in New Jersey and New York, and (4) bus lanes on various bridges in the San Francisco Bay Area. Most of these facilities were eventually converted into high occupancy vehicle (HOV) facilities to improve their utilization. Primary factors that contributed to these

systems not utilizing the entire BRT toolbox of strategies include (1) insufficiently developed or cost-effective technologies and (2) lack of political will to champion their use. Domestically, during the following two decades interest in BRT generally waned as the US transit industry’s mode of choice for high traffic corridors tended toward rail-based projects [6].

International Experience

During the 1960s, Curitiba, Brazil, experienced rapid population growth of approximately 3% per year due to large in-migration from rural surroundings resulting in overwhelming traffic congestion. A 1965 regional plan called for the establishment of developmental policies for transportation whose goal was to encourage growth patterns that would be sustainable and supportive of a viable public transit system. The plan called for a mono-centric city with four radial corridors that would bear most of the burden of growth and development in the region. Lacking adequate financial resources for a rapid rail “Metro” system, an approach taken by many of its larger neighboring Latin cities, Curitiba opted for a Bus rapid transit system. Whereas, an underground Metro was priced at approximately \$60–\$70 million dollars per kilometer (\$97–\$113 million dollars per mile) (1,965 \$US), the express bus roadways were only \$200,000 per kilometer (\$323,000 per mile) [9–11].

The busway opened for service in 1972, and incorporated many, if not most, of the features outlined in Crain’s paper [4, 5]. The system relied on features such as a high or raised boarding platform to match the vehicle floor height [12], pre-boarding fare payment, signal priority, onboard automated announcement systems [12] and high-frequency service to ensure high-quality Metro-like service. Over the last 30 years, Curitiba has been able to incrementally expand and upgrade the system as funding allowed and demand warranted. Instituting strong land use controls, the government has also been able to effectively guide growth to encourage development patterns along structural axes that reinforce and encourage use of the bus system. This has kept Curitiba’s central city both a vibrant and a pleasant urban environment.

With the success in Curitiba, several other developing Latin American cities such as Sao Paulo, Brazil,

Porto Alegre, Brazil, and Quito, Ecuador, have since implemented systems based on the Curitiba public transit model.

Similarly, Ottawa, Canada also turned to the Bus rapid transit concept when it decided to upgrade its transit system. Ottawa made the decision to use the bus as the backbone of the city's transit system, and started its "Transitway" in 1973 with approximately 6.8 miles of bus lanes. By 1983, the first of several busways were opened providing buses with exclusive, grade-separated right-of-way. By 2000, the system utilized 16 miles of exclusive right-of-way, approximately 7.8 miles of priority lanes, and 2 miles in mixed traffic with nearly 200,000 trips per day capable of carrying 10,000 riders per hour in each direction [6, 13].

The Transitway has features that make it special. In the outlying areas away from the urban core, the Transitway's right-of-way is an exclusive bus lane that is at- and above-grade depending on location usually with one lane per direction. At each station, the right-of-way expands to two lanes per direction to allow for buses to stop without blocking other buses. Moreover, at some locations, the exclusive right-of-way is directionally separated by barrier or a grassy median. In a few locations, the bus uses the freeway for short distances (1–2 miles) in an exclusive bus lane. This lane is the freeway's right-most lane that is an exit-only lane for use only by Transitway buses. It is separated by means of a virtual barrier with diamond symbols painted on the bus lane. Some of the Transitway's stations have similarities to rapid rail stations, not in the sense that they are underground (in fact, there is only one tunnel station on the Transitway's route), but that they are infrastructurally extensive. For example, some of these stations are adjacent to commercial office development and are linked together via enclosed walkway bridges. At one location, the Transitway has a stop immediately outside a major department store that is part of a suburban mall. The extensively built stations are fully enclosed to accommodate Ottawa's winter weather with multiple stops for entry onto and exit from buses. Also, bus routes for non-Transitway lines converge at several of the Transitway's stations. In addition to the Transitway's connection with Ottawa's International Airport, it also connects with Ottawa's central train station via an enclosed walkway bridge linking the two stations [6].

Ottawa is typically heralded as another shining success story for bus rapid transit and several other Canadian cities have since embraced this concept. Though most do not use exclusive right-of-way, projects in cities such as Montreal, Quebec, and Vancouver, British Columbia have turned toward advanced technologies, in lieu of exclusive facilities, to achieve higher bus performance.

The Return of Bus Rapid Transit to the USA

During the late 1970s, BRT made a comeback to the USA with the implementation in Pittsburgh, Pennsylvania of the first of three major segments of its busway system. In 1977, the 4.3-mile South busway became operational followed in 1983 by the 6.6-mile East Busway with a 2.3 mile extension in 2003; in 2000, the West busway – 5 miles in length – officially opened. This busway system, combined with several new Light Rail Transit projects, has produced an integrated, multimodal system for the greater metropolitan Pittsburgh area [14]. Bus rapid transit success stories in cities such as Curitiba, Ottawa, and Pittsburgh, coupled with continuing congestion and air pollution in urban areas have sparked a renewed interest in the bus rapid transit concept. In 1998, the US Department of Transportation's Federal Transit Administration initiated support for ten BRT demonstration projects, which helped generate further interest in bus rapid transit [15–17].

Contents of This Entry

This entry begins with a discussion of institutional issues associated with the implementation of bus rapid transit systems from a macroscopic perspective. Initially, issues were organized into categories including, for example, intergovernmental and interorganizational, political will, and land use. The subsequent discussion of each category follows with a listing of specific institutional issues within each category.

The entry then turns to a more focused look at specific institutional issues that, based on experience, stand out from other issues relative to the following two criteria: level of importance and level of difficulty to resolve. Specific examples are provided in this section of the entry to illustrate issues.

Institutional Issues: A Broad Perspective

The implementation of bus rapid transit systems traverses numerous stages consisting of system design, development, testing, evaluation, and deployment culminating in a completed and fully operational system. Moreover, all these activities take place in a context with organizational stakeholders participating at various levels. In fact, an overriding theme running through the BRT implementation process is the notion of stakeholders, their agendas, and the relationships among them. As each stage of BRT implementation proceeds through its more technological, design, and operational aspects, questions may arise concerning the effects of actions taken or policy decisions made, which are often of a nontechnical nature and usually referred to as *institutional issues*. These less-technical and less-operational issues, which are numerous and diverse, need to be considered and effective arrangements made that address them to successfully implement a bus rapid transit system.

Bus rapid transit systems will not necessarily experience the same set of institutional issues because each BRT deployment will be affected by local and regional factors. Moreover, even when the same issues arise in different settings, there will likely be local and regional site-specific differences. The importance of identifying and working out such issues should not be underestimated as they do contribute to the overall success of implementing bus rapid transit systems in terms of how transit operations and quality of service for passengers are enhanced.

Institutional issues may be grouped into the following general categories [6]:

- Intergovernmental and Interorganizational
- Intra-agency
- Political Will
- Public Relations and Marketing
- Funding and Finance
- Labor and Human Factors
- Safety and Liability
- Land Use and Planning
- Physical Environment

Intergovernmental and Interorganizational

It is rarely the case that a transit agency can develop a bus rapid transit system without the coordination

and cooperation of multiple agencies and often overlapping governmental jurisdictions. Even if this were possible, there is benefit in seeking the cooperation and support of other agencies. However, the multi-jurisdictional and/or multi-stakeholder aspects can make the process of decision-making and implementation more complex as each stakeholder usually brings their own philosophies, priorities, and agendas to the table. Achieving agreement among all affected stakeholders – whether political jurisdictions or other transportation organizations – often proves to be a difficult task. To have a system that works effectively requires the transit agency to achieve agreement with localities and other agencies on infrastructure, operations, and responsibilities.

When planning for the deployment of bus rapid transit systems, there are, at a minimum, two distinct types of stakeholders with primary roles. One is the local and/or regional transit agency whose interest lies foremost in reducing its own costs while also enhancing the quality of transportation services that it delivers to its passengers. The other primary stakeholder is the local and/or regional highway and traffic department along the route the transit agency's bus runs and this latter stakeholder could include multiple operators depending on whether the bus runs through multiple political jurisdictions. Other stakeholders with a role to play in the implementation of bus rapid transit might also include the following agencies and/or organizations [18]:

- Municipal environmental, health, and urban development and public works departments
- Construction industry and other potential industry supporters
- Regional and/or metropolitan planning organizations
- State or provincial department of transportation
- Relevant national or federal transportation agencies, for example, in the USA such agencies include the Federal Transit Administration and Federal Highway Administration
- Advocacy groups, for example, proponents of competing or complimentary rail projects
- Motorists and their representative organizations
- Economic development agencies
- Business and merchant associations

- Neighborhood or corridor resident associations
- Traffic and transit law enforcement
- Public transportation experts and consultants
- Nongovernmental organizations
- Public transportation passengers, for example, the Bus Riders Union in Los Angeles, California
- Nonmotorized transportation users
- General public

The significance of these stakeholders' roles and influence depends on local and regional conditions encompassing the bus route/traffic corridor where the bus rapid transit system is to be implemented.

Typically, a public transit agency will interface with other government agencies during regular service discussions; however, these interfaces become more critical with the development of a bus rapid transit system; it is typical for a public transit agency to need to coordinate with an organization it had not worked with prior to the bus rapid transit project. These agreements should set out agency and staff responsibilities giving particular attention to the clarification of roles. Achieving consensus, let alone agreement, among all affected stakeholders, whether political jurisdictions or other transportation organizations may at times prove to be a challenging and possibly difficult task. To have a system that works effectively requires the transit agency to achieve agreement with localities and other agencies on infrastructure, operations, and assignment of responsibilities. However, the primary objectives of transit agencies – to provide high-level, high-quality service for their customers at minimum cost – may conflict with the objectives of highway and traffic agencies whose performance is often judged more on enhancing vehicle-moving than people-moving capacity. These often-competing objectives can complicate the implementation of bus rapid transit strategies and may require significant coordination and cooperation if multiple transportation and traffic agencies are involved. An example of conflict of objectives occurs when a BRT project is planned to operate in mixed traffic on public running ways such as when working to achieve the operational benefits of BRT service, preferential treatment on the running way is often required.

The selection and incorporation of new BRT infrastructure may also prove difficult. For many projects, public transit agencies are “tenants” of streets or

highway departments, often dependent on the cooperation of the roadway operator for the right to use their infrastructure such as the roadway, signal poles and boxes, etc. Many BRT strategies also utilize infrastructure, which not only needs to be incorporated into the existing roadway facilities, but must be operated and maintained as well. With new infrastructure come additional financial responsibilities. Reaching agreement on acceptable designs, and operational and maintenance responsibilities would likely involve coordination among these agencies.

Bus rapid transit operations will be effective only if laws and regulations regarding transit prioritization are enacted, adhered to, and enforced. Effective enforcement carries with it financial responsibilities that may be thrust reluctantly upon local jurisdictions. Infrastructure and enforcement are two factors vital to the success of BRT, which often lie outside the control of the transit agency. Enlisting the support of the affected parties in these two areas may ultimately determine the success and effectiveness of the BRT system.

Bus rapid transit prioritization may also occur at the expense of other roadway users such as in the case of queue jump lanes. This issue will require discussion and agreement on where and how these preferences should be given, while considering its impact on existing roadway operations. Any impacts to existing services will require the consent and support of highway agencies or street departments, and local governments.

Finally, in attempting to make a seamless transit system, BRT services should be coordinated with neighboring transit agencies. This may require them to revise their operations and schedules to provide better feeder services for the BRT system.

The number and complexity of the agreements will depend upon the type of facility and the governmental organization(s) in the area. There are generally a number of elements of the system that are out of the control of the transit agency. Cooperation among agencies is critical to the successful introduction and operation of a BRT system. In these cases, it is necessary to define and codify these responsibilities. Intergovernmental agreements will be required with a number of different agencies covering items such as right of use (how long, conditions for extension or termination of agreement, state in which the facility is returned to the

appropriate agency, legal responsibility, watering maintenance of landscaping, maintenance of running ways, trash collection, graffiti removal, advertising, enforcement, signal timing, lighting). In some cases, local or state laws may be enacted, repealed, or modified to implement various BRT elements or practices, such as the use of the BRT facility by emergency service vehicles.

A specific example to illustrate this type of institutional issue brings together technological aspects, operational plans, and institutional concerns of implementing bus rapid transit. For Los Angeles' Wilshire-Whittier Boulevard Metro Rapid service, which opened in 2000, the Metropolitan Transportation Authority (MTA) implemented a number of bus rapid transit features as elements of its Metro Rapid service including transit signal priority along the heavily traveled corridor, which traverses the cities of Santa Monica, Beverly Hills, and Commerce in addition to the city of Los Angeles and each of these municipalities controls traffic signal operation within their respective jurisdictions. Moreover, along the corridor, the municipal boundaries are such that the city of Los Angeles is interspersed among the other three municipalities in a noncontiguous fashion. Thus, for the Wilshire-Whittier corridor, MTA and the four traffic signal operators, that is, the local municipalities, are the primary stakeholders. Initially, transit signal priority was implemented only within the city of Los Angeles as the other cities wanted demonstrative proof of transit signal priorities' benefits before relinquishing control over the operation of traffic signals in their jurisdictions. To date, transit signal priority still remains implemented only in the city of Los Angeles while negotiations between MTA and the other jurisdictions continue.

The following list summarizes intergovernmental/interorganizational institutional issues:

- Integration of multiple priorities, objectives, and agendas
- Impacts of BRT on roadway operations
- Streets/highway departments "relinquishing" control of their infrastructure
- Agreement on performance measures
- Maintenance responsibilities for shared infrastructure and hardware/software
- Responsibility for enforcement on bus lanes/busways
- Institutional fears of new technologies
- Coordination on selection and implementation of technologies
- Coordinating other transit agencies' services and BRT operations

Intra-agency

Institutional issues may arise not only among transit agencies, political jurisdictions, and highway traffic agencies, but also internally within an individual transit agency. Concerns over preferences in funding and scarce resources, the delegation of responsibilities, and increased responsibilities for staff may result in internal resistance and morale issues for a transit agency. Unless there are additional funding sources available, increased spending on one route will usually mean decreased funding on others.

Bus rapid transit systems may require additional resources to support the service offered. Additional operations, new technologies, new vehicles, and new infrastructure will require training and maintenance. Achieving agreement on roles and responsibilities may be difficult if employees are merely required to shoulder additional duties and responsibilities for BRT without additional compensation or support.

Many transit agencies may still be unfamiliar with at least a portion of available BRT strategies and agencies may need time and resources to locate or develop both design and operational standards for many of these strategies. Initiating BRT service may also require additional work to reschedule existing services to support the BRT system. As many BRT systems will operate as trunk lines, feeder services will need to be coordinated to achieve the full benefit of the system.

Even gaining internal agreement on what strategies should be implemented, what fare structures should be used, and what technologies are appropriate will again require time and resources. Many agencies will need additional time to identify and digest best industry practices for these issues. Even then, identifying and attempting to accommodate a transit agency's departments' needs may cause internal conflict. As new strategies may affect the duties of department staff, it is vital

that they are consulted and strategies are selected with their concerns in mind.

The following list summarizes intra-agency institutional issues:

- Concerns (or perceptions) that BRT is given special preference over other transit services
- Defining and agreeing on new roles, responsibilities, and organizational structures to support BRT
- Creation of design and operational guidelines for BRT
- Determining an appropriate fare structure and medium
- Internal coordination on selection of technology
- Coordinating schedules of other transit routes with BRT operations
- Insufficient understanding of the “state of the art” of technologies and how they can be used in BRT operations

Political Will

The deployment of a bus rapid transit system is one of many stages in the process of design, development, testing, evaluation, and finally deployment of a completed system. At each stage, decision-making stakeholders are involved in a variety of ways that impact the specific deployment path a particular bus rapid transit system will take. The decision-makers are by definition major players in the political arena that govern the local jurisdictions in which the bus rapid transit system would operate. The commitment to bus rapid transit by such major players is of crucial importance to the success of a bus rapid transit system.

One concern in the political arena may be whether a proposed bus rapid transit system is a solution in search of a problem, whether appropriate technologies are being used, and whether there is a market for these enhanced bus transit services. Does it result from a technology push or market pull?

To establish and sustain a high level of interest and commitment to BRT, a political champion will likely be required. Whether it is an individual or organizational entity, a political champion would aid in coalition building and sustaining interest in BRT, which could wax and wane with the whims of the political process.

The strength and capability of the political champion would help determine if the project could weather the political storms of opposition arising from various quarters, for example, the local business community, the mass media, or local residents. However, gaining such championing decision-makers often requires proof of the operational and quality-of-service benefits of BRT, but political support is required to perform the testing that could result in the quantifiable benefits, resulting in a chicken-or-the-egg dilemma requiring resolution.

There may also be issues regarding legislative restrictions on the procurement of new vehicles that could delay or slow deployment of BRT. Legal issues may also arise as a result of changes in service associated with BRT operation. For example, route changes, the elimination of stops, or lengthening the distance between consecutive stops could potentially present legal challenges.

Many political officials may be reluctant to undertake a bus rapid transit project due to the perceived risks, especially in relation to upsetting powerful special interest groups. For example, motorists and existing public transportation operators may tend to resist such change. Thus political officials may end up playing it safe by avoiding any type of major public transportation initiative that will risk alienating specific stakeholders. However, when officials take the perceived low-risk path of inaction or very slow action, the ensuing political rewards will certainly be reduced [18].

The following list summarizes politically related institutional issues:

- Concerns of BRT being a top down solution
- Perceived or actual competition of BRT with rail transit
- Lack of domestic BRT success stories
- Lack of empirical evidence of BRT’s operational effectiveness
- Finding political champions to support BRT
- Concerns over long-term level of interest, potential for waning
- Local and business community opposition to the removal of, or restrictions on, parking spaces for BRT use
- Local and community opposition to BRT

- Concerns over the distribution of the costs and benefits of BRT
- Legal issues associated with service changes
- New vehicle procurement

Public Relations and Marketing

The success of implementing a bus rapid transit system, as with nearly any new product, service, or system, largely depends on how well it is sold to the public, which often requires setting expectations. Setting high, yet realistic expectations is crucial to gain support for BRT. Failure to produce what was promised could lead to disappointment and a loss of public confidence and support. Bus rapid transit may also require a significant public education campaign on interacting with new transit agency strategies, features, and technologies such as bus lanes, signal priority systems, queue jump lanes, and new fare-collection systems. Moreover, the transit agency needs to consider public views about its current performance. Before taking on the additional responsibilities of a BRT system a transit agency must ensure it is performing satisfactorily, or it could face political and public opposition as it embarks on new ventures [19].

The following list summarizes public relations and marketing institutional issues:

- Educating the public on BRT, and managing perceptions and expectations
- Concerns over transit agency's existing performance and reputation
- Concerns over effects of BRT on existing roadway operations
- Educating pedestrians and motorists on interacting with BRT
- Educating users on changes in and uses of multiple fare structures

Funding and Finance

During the 1960s and 1970s, interest in BRT in the USA waxed and waned. Though there is renewed interest, the fear of history repeating itself in the USA may still cause concern among transit agencies considering BRT for their communities and lead to their reluctance to embrace bus rapid transit. Though the up-front capital costs for most BRT projects are relatively small

compared to other capital-intensive modal alternatives such as rail, transit agencies will still be responsible for the operations and maintenance of the new system. With continued fiscal pressures facing transit agencies, concerns may arise over the long-term financial commitment to bus rapid transit. Similarly, bus rapid transit will also require additional financial commitments for staff, training, and enforcement [19].

The following list summarizes funding- and finance-related institutional issues:

- Concerns over long-term funding commitments to BRT at the state and federal levels
- Concerns about BRT redirecting funds away from existing service or other routes
- Lack of understanding of funding mechanisms available for BRT
- Agency reluctance to expand services due to current fiscal constraints
- Ability to use existing buses or need for new fleet
- Capital costs of BRT
- Cost of operating and maintaining (O&M) new technologies and infrastructure
- Cost of additional staff and/or training to support BRT
- Cost of additional facilities to support BRT
- Cost of and responsibility for enforcement, for example, proof of payment

Labor and Human Factors

Another important stakeholder group that must be considered for bus rapid transit is the transit agency staff, especially bus drivers. What will be the impact of bus rapid transit on bus drivers? With the implementation of bus rapid transit, there could be concerns over additional work and responsibilities without assurances of additional staff, needed resources, and/or pay. Bus drivers would have a direct and potentially the closest connection of all agency employees to any new technologies implemented as part of a bus rapid transit system. How would such technologies affect bus drivers? Would it mean any change in the roles and responsibilities of their job? Could the implementation of a bus rapid transit system mean that some bus drivers would lose their jobs or be replaced by individuals with more familiarity with and experience in the use of certain technologies? Will there be assurances to

retrain and reeducate bus drivers to use these new systems?

Another concern of bus drivers could be the use or perceived misuse of technology by transit agency management for driver performance monitoring. Drivers may fear their employers using “Big Brother” privacy-threatening tactics under the guise of improving transit operations and service [19].

The following list summarizes labor-related institutional issues:

- Lack of support from transit agency staff
- Changing role of drivers
- Use of technology, for example, automated vehicle location systems for monitoring schedule adherence
- Different responsibilities between bus rapid transit and non-BRT routes

Safety and Liability

Bus rapid transit may involve new procedures, technologies, or personnel tasks. The potential thus exists for system components not to function as anticipated, raising safety and liability issues. Stakeholders need to consider whether bus rapid transit changes the assignment of risk and responsibility if technologies or strategies do not function as intended. Safety issues regarding pedestrians and motorists and their interaction with bus rapid transit components, such as signal prioritization and queue jump lanes, will also need to be considered and addressed [19].

The following list summarizes safety- and liability-related institutional issues:

- Insurance industry-initiated changes in assignment of risk and responsibility for bus transport
- Potential changes in liability associated with technological and/or operational malfunctions of BRT systems
- Safety issues arising from changing interaction of pedestrians and motorists with new technologies and/or strategies
- Safety concerns of residents along BRT corridors

Land Use and Planning

Large-scale public transportation projects often influence travel patterns and surrounding land uses, over

both the short and the long term. Bus rapid transit would be no different, as high-level transit services, which BRT attempts to replicate, have often significantly altered surrounding land uses. However, bus rapid transit may raise concerns over how it fits into a region’s overall transportation planning environment and how it will affect local land uses.

Anecdotally most transit planners believe that fixed guideway systems have a positive impact on land use, particularly around the station areas, whereas bus-based systems have at best a neutral impact. Bus-based systems have been shown to have a beneficial impact at a community level; however, property adjacent to stops/stations is considered less desirable.

One of the biggest concerns of communities developing bus rapid transit systems is convincing them that BRT will provide the benefits that they associate with fixed guideway modes. The advent of BRT systems has challenged this premise. The new BRT systems that have chosen to incorporate a fixed guideway element have demonstrated that bus-based transit systems can have a positive impact on urban form and land values. Although the BRT concept is still relatively new in the USA with only a handful of systems in operation, there is a growing body of evidence that suggests that BRT systems can support existing land users and promote higher density residential, office, and commercial land use, particularly around BRT stations. North American examples of this trend include Boston, Pittsburgh, and Ottawa, where \$1,250 million, \$302 million, and \$675 million of new or improved development, respectively, has occurred. The continuing development of more BRT systems will provide further evidence of this effect; however, as land use improvements tend to lag transit investment, examples of this trend may take a while to be realized [20].

Some BRT systems have benefited by initially developing a number of key stations where land use development potential exists and linking them with transit facilities which incrementally increase to fully exclusive busways. In this way, they could make strategic infrastructural investments at specific locations without the need to improve the whole corridor to the same level.

The following list summarizes land-use- and planning-related institutional issues:

- Coordinating a BRT project with local planning agencies' land use policies
- Gaining community support for transit-oriented development
- Possible reluctance of potential developers to invest along BRT corridors due to a perceived lack of permanence as compared to rail
- Integrating BRT projects into the metropolitan planning process
- Planning requirements such as transportation improvement programs that could delay implementation of a bus rapid transit system
- Need for strong community involvement in planning phases builds support

Physical Environment

The physical imposition of a BRT system may also raise political and institutional challenges. Many project areas, especially in older city centers, may simply lack the physical space to accommodate certain BRT strategies. In other areas, transit agencies may encounter opposition if BRT competes with, or at least is viewed as competing with, other interests for high-value real estate. This may inflate costs or overly complicate operational requirements. Though eminent domain is an option, it usually is an undesirable, drawn-out process. Ensuring there is adequate and obtainable physical space could present problems for certain projects.

Secondly, image is a strong marketing tool for BRT. Many design guidelines suggest making the system unique and easily identifiable. Many projects are included as part of their systems station area improvements. However, these improvements are usually being inserted into existing urban design. Finding station area designs that promote a strong image, while being acceptable to local interests, may be a challenge.

The following list summarizes physical-environment-related institutional issues:

- Availability and acquisition of right-of-way or physical space
- Reaching agreement or consensus on bus stop/station area enhancements
- Need to educate and address public concerns regarding the potential effects of BRT on the physical environment

Institutional Issues: Stakeholder Experience

Transit agency experience has shown that there are specific institutional issues that are primary and stand out from others with respect to the criteria of level of importance and ease of resolution. Eight primary issues are listed below (in no particular order) [21]:

1. Local and business community opposition to the removal of/restrictions on parking spaces for BRT use
2. Availability and acquisition of right-of-way or physical space
3. Integration of multiple priorities, objectives, and agendas
4. Concerns over long-term funding commitments to BRT
5. Impacts of BRT on roadway operations
6. Finding political champions to support BRT
7. Gaining community support for transit-oriented development
8. Educating the public on BRT and managing perceptions and expectations

Integration of Multiple Priorities, Objectives, and Agendas

The integration of multiple priorities, objectives, and agendas often lies at the heart of institutional issues. When several institutions come together to discuss issues of common interest, each brings its own organizational experiences, cultures, and goals. A "win-win" strategy might not always be achievable, but BRT project members need to acknowledge and be thoughtful of other agencies' issues and concerns. Modal biases and agendas have historically infiltrated transportation planning. However, in recent years, with the recognition that multimodal transportation systems tend to be the healthiest, there are greater levels of cooperation. Many transportation organizations, however, still have responsibilities to their respective agencies or jurisdictions, and are still expected to protect their own interests. Though greater cooperation nevertheless must also be accompanied by continuous dialogue to discuss and better understand stakeholders' concerns and by attempts to address them throughout the BRT development and implementation process.

For example, close working arrangements between traffic engineers and transit planners are essential in developing busway and bus lane designs, locations of bus stops and turning lanes, and application of traffic controls. A good program of traffic controls and signage will help ensure safe vehicle and pedestrian crossings of busways and bus lanes. Excessively long traffic signal cycle lengths to accommodate exclusive bus phases should be avoided.

Los Angeles's successful Metro Rapid bus operations on its Wilshire-Whittier and Ventura Boulevard lines are a direct result of cooperation between the MTA and the city's Department of Transportation (DOT). These two agencies found that (1) a modest "advance" or "extension" of the traffic signal green time (or a delay of the red signal time) of up to 10 s per cycle can reduce bus delays with negligible impacts on cross street traffic, (2) bus headways should not be less than 2.5–3.0 min to enable major cross streets to "recover" from the time lost, and (3) far-side stops are essential.

An at-grade busway has fewer traffic impacts on intersecting roads than a typical arterial street. However, relatively light bus volumes require traffic control strategies that ensure safety at grade crossings. Positive protection, such as bus-actuated traffic signals, is essential. However, if accidents persist, gating of bus crossings may be appropriate. The busway should be treated as though it were a high-speed light rail line on a private right-of-way. If there is sufficient conflict among various modes (i.e., vehicles, transit vehicles, and pedestrians), it is important to incorporate gates to reduce these conflicts [1].

Finding Political Champions to Support Bus Rapid Transit

Though public support is critical in implementing a BRT system, it is usually not attainable through transportation agencies alone. Finding a political champion to support a BRT initiative may be critical in gaining public support. Politicians are typically the final decision-makers and often have the clout to produce results. Gaining the ear and voice of influential politicians is one of the most often-cited means of achieving results [19].

Roadway-Related Issues

The following three issues may be covered under the umbrella of *roadway-related issues*:

- Local/business community opposition to removal of/restrictions on parking spaces for BRT use
- Availability and acquisition of right-of-way or physical space
- Impacts of BRT on roadway operations

Bus rapid transit intends to provide the high-quality service associated with rail transit at a much lower cost. In many BRT projects, this is accomplished by providing buses with exclusive or nearly exclusive right-of-way, so operations are not affected by urban street congestion. However, obtaining the required right-of-way may be difficult. Most BRT projects operate, for at least a portion of their route, in developed urban areas where physical space for transportation improvements is typically not in abundance. In several projects, this space comes from currently utilized roadway lanes or from existing parking lanes. Operators of the roadway facilities (typically municipal streets departments or state departments of transportation) used for BRT projects will be interested in how BRT operations would affect their facilities. In cases where projects look to utilize roadway space that is currently on-street parking, businesses and residents may be opposed to the "loss" of parking, even if it is only for peak-period directions and times. For example, at BRT stops/stations the use of queue jump lanes and/or bus bulbs may also be considered. The use of these design attributes in order to improve the level of service may, however, conflict with concerns of the local business community over its opposition to the removal of or restrictions placed on parking space availability that may be necessary to accommodate such operational and service plans for BRT. Therefore one of the major institutional considerations in assessing where BRT is a realistic alternative for specific corridors or roadway facilities is the availability of physical space to accommodate BRT operations. Proper consideration must be given to identify whether there are competing interests for space and how BRT operations may impact these facilities [19].

Concerns over Long-Term Funding Commitments to BRT

Concerns over long-term funding commitments to BRT include it merely being the popular favorite and the implications for transit agencies should the BRT concept fall out of favor. Some BRT projects will require a great deal of capital investment, often

requiring transit agencies to shoulder the risk of having greater capital to maintain without recovering sufficient additional revenue to cover those costs. Whether these are items that a transit agency can afford to operate and maintain, may cause reluctance on the part of transit agencies to embrace BRT [19].

Gaining Community Support for Transit-Oriented Development

Allaying the fear of the unknown is often a responsibility that must be borne when presenting an untested concept to the public. Many BRT projects have incorporated land use strategies to encourage and reinforce transit usage. However, for most outside of the transportation and planning communities, the concept of transit-oriented development (TOD) is new. For many, higher density and mixed use equals more crowding and greater congestion. Attempting to obtain public support for TOD may be a challenging undertaking, especially if there are not many local examples to aid the public's understanding. Proactively educating the public on the underlying objectives of TOD may assist a transit agency in avoiding public opposition to it [19].

Educating the Public on Bus Rapid Transit, and Managing Perceptions and Expectations

This issue may be critical in maintaining continued support of and interest in bus rapid transit. Agencies must perform a balancing act on this issue. For BRT to be embraced by both the public and the decision-makers, the concept must be "sold" to them but it must be sold in the correct manner and amount. Setting unrealistically high expectations can lead to disappointment and a loss of support both from the public and from the decision-makers. It is important that balance be maintained between the "hype" and actual results.

Future Directions

Throughout the world, bus rapid transit systems continue to be implemented, with more than 135 systems in over 28 countries on 6 continents and 90 cities in North and South America, Europe, Asia, Australia, and Africa in both the developed and developing worlds. In the USA alone, there are nearly 60 existing BRT systems with significant progress made in the number of implemented systems in the last 12 years alone, which marks a special

milestone year in the history of BRT in the USA because 1998 was the start of the most recent resurgence of interest in the USA in bus rapid transit with the US Department of Transportation's formal initiation of and support for a US BRT Demonstration Program.

BRT has shown that it is indeed a viable rapid transit mode within the USA. The strength of the mode lies in its diverse range of BRT strategies and its flexible and incremental character of deployment that allows transit agencies to customize their BRT system to the local environment including institutional concerns, available right-of-way, or traffic conditions.

For example, agencies with both budget and time resource constraints and little, if any, additional right-of-way capacity may consider a BRT system modeled after Los Angeles's Metro Rapid service. The Metro Rapid uses lower-cost strategies including ITS technologies (transit signal priority systems), frequent headway-based service, a branded and unique identity for the buses and bus stops, low-floor buses, real-time passenger information systems, and a simple route structure with fewer stops to minimize total travel time and enhance travel time reliability on mixed traffic urban arterials. If additional right-of-way capacity is available, agencies may want to consider implementing services on dedicated bus lanes within existing roadways, such as the EmX Line along the Franklin Avenue corridor between Eugene and Springfield, Oregon, where a traffic lane was converted for BRT use. Another example is the Healthline BRT system along the Euclid Avenue corridor in Cleveland, Ohio, where one traffic lane per direction along its 4.5 mile long corridor was removed to build a bus lane within the median. With still more available right-of-way, on the high end of the roadway capacity continuum are exclusive running ways, such as the Metro Orange Line in Los Angeles built along a 14-mile former rail right-of-way owned by MTA. Such systems offer the greatest potential for achieving high speeds and high levels of travel time reliability required for and desired by public transit choice riders.

The next decade will continue to see more BRT systems implemented on an international scale especially in the developing world. In the USA, BRT will continue playing a major role in transit systems throughout the country. Cain A, et al. [22] have suggested that if current trends continue in pioneering BRT cities such as Los Angeles, which has already

implemented a network of approximately 25 Metro Rapid BRT Lines beginning with its initial deployment of the Wilshire-Whittier and Ventura Boulevard Lines in 2000, the next major challenge will be transitioning from individual BRT corridors into integrated networks of BRT routes. Such expansion offers transportation planners and engineers the opportunity to increase the benefits of BRT from the corridor level to the city or regional level, enhancing public transit ridership that helps improve mobility and air quality, reduce congestion, and promote economic growth. Careful integration of such networks with existing BRT and conventional bus services as well as non-bus transit modes will be crucial to achieving a successful transition. Nonetheless, in the context of a BRT network as opposed to an individual BRT corridor, the institutional structure may experience changes and it is possible that additional institutional issues heretofore not identified may arise or already existing issues may be exacerbated, which of course will need to be addressed as part of any successful BRT network implementation process.

Acknowledgments

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Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues

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Glossary

Alternatives analysis Evaluation of different transit choices available, usually requiring cost-benefit analysis, life cycle costing, and sensitivity analysis.

Branding Name, term, design, symbol, or any other feature that identifies a service or product.

Bus corridor A street or highway featuring bus priority measures, such as bus lanes or busways or traffic signal priority.

Bus lane Street or highway lane(s) with priority designation for bus public transport services.

Bus priority Infrastructure or traffic signal measures to speed up bus public transport services, especially at intersections or junctions.

Busway Street or highway lane(s) exclusively designated for bus public transport services.

Comfort The capacity to give physical ease and well-being. In public transport, it is usually related to the provision of adequate space, soft ride, easy circulation, and adequate information for passengers.

Commercial speed Distance traveled divided by the time, as perceived by the passengers of the public transport system. It includes time spent at bus stops or stations, intersections or junctions, and the time traveling between them.

Externalities An economic effect that is not reflected in market prices. In public transport, this term usually refers to travel time, air pollution, road fatalities and injuries, and other effects on people and the environment.

Fare collection Collection of entrance fee in a public transport service. It may include direct access to the service or tickets or passes to travel.

Headway Time interval between two consecutive transit vehicles.

Intelligent transport system (ITS) Is an umbrella term for a range of technologies including processing, control, communication, and electronics that are applied to a transportation system.

Paratransit Is an alternative mode of flexible passenger transportation that does not follow fixed routes or schedules. It includes informal services as well as formal services provided for users with special needs, such as elderly and disabled.

Passenger capacity Number of passengers that can be accommodated in a vehicle, station, service, or section of the transport system. Can be measured in units of space (passengers per square meter), vehicles (passengers per bus), or time (passengers per hour per direction).

Peak section load Number of passengers riding inside the transit vehicles in the heaviest section of the public transport system and direction per unit of time, usually 1 h.

Public transport Is a shared passenger transportation service which is available for use by the general public. Also known as public transportation or transit.

Public-private partnership Describes a government service or private business venture which is funded and operated through a partnership of government and one or more private sector companies. These schemes are sometimes referred to as PPP or P3. In public transport, this term usually describes the service or concession contract for transit provision, which may include development of infrastructure and vehicles.

Rapid transit A system of public transport in an urban area, using a combination of infrastructure, vehicles, operations, and information technologies to provide fast and reliable service.

Reliability Capability of being relied on; dependability. In public transport, this refers to the provision of timely services, with low variance in arrival and travel times.

Service operation plan Public transport routes, schedules, and itineraries, preferably planned in advance and centrally controlled to provide service according to the user needs.

Traffic signal Signaling devices positioned at road intersections, pedestrian crossings, and other locations to control competing flows of traffic. Also known as traffic lights, stoplights, traffic lamps, traffic signals, or semaphores.

Transit-oriented development (TOD) Urban area designed to maximize access by public and nonmotorized transportation to encourage transit ridership. A typical TOD has a rail or bus station at its center, surrounded by relatively high-density and mixed used development. It usually has adequate facilities and attractive street conditions for walking and cycling, good connectivity, and uses traffic calming and parking management measures.

Definition of the Subject and Its Importance

Bus rapid transit (BRT) can be defined as a flexible, rubber-tired form of rapid transit that combines stations, vehicles, services, running ways, and information technologies into an integrated system with strong identity [1]. Complete BRT systems offer fast, comfortable, and low-cost urban mobility [2]. BRT is an evolution of bus priority measures, such as designated busways and bus lanes, which were proposed, and in some cases implemented, as early as 1937 throughout the world [3]. The expression BRT was initially used in the United States in a 1966 study [4]. The concept gained popularity in Latin America after the successful upgrade of busways in Curitiba, Brazil, to full-featured BRT in 1982 [5]. The high performance, low cost, and rapid implementation of this system, and its adaptations to Quito, Bogotá, Mexico City, Beijing, Jakarta, Los Angeles, Beijing, Istanbul, and Guangzhou, among other cities, made the idea attractive for urban

transport planners throughout the world. As of January 2011, there were about 118 cities with BRT or bus corridors, with 97 of the cities entering into the list in the last 10 years, and at least 80 cities building, designing, or planning BRT systems [6]. BRT is an attractive option for public transport delivery, applicable to a wide variety of conditions – from very low to very high passenger throughput, and should be considered in alternatives analysis in most transit corridors. Critics of BRT indicate that these systems are not permanent, use precious surface space, and exhibit operational and cost issues as compared with rail [7]. BRT implementation requires strong political leadership, sound technical planning, and adequate funding levels [2, 8].

Introduction

The concept of BRT is not new [3], but it has only been extensively deployed around the world in the last decade [6]. The growth may be attributed in part to the success of Curitiba [5] and its adaptations in different parts of the world [2, 3]. In general, BRT systems exhibit low cost, rapid implementation, and high performance, with significant positive impacts [2, 9].

Interesting trends are emerging in the BRT industry [6], such as the implementation of citywide integrated bus systems based on BRT, improved processes for private participation in operations, increased funding from national governments, and growth of bus manufacturers and technology providers. Technological developments in vehicles and information systems are also improving the quality, performance, and impact of BRT [9].

Despite the growth, there are some outstanding issues: BRT does not have a single meaning and image and it is often regarded as a “second best” as compared to rail alternatives [2]. Its ability to foster urban development and the use of space designated for cars are often questioned, as well as its actual costs and impacts [7]. In addition, several systems in the developing world suffer problems resulting from poor planning, implementation, and operation, due to financial, institutional, and regulatory constraints [8].

This entry discusses the concept, its history, and expected trends. In the first section the concept of BRT is developed. The following sections show the

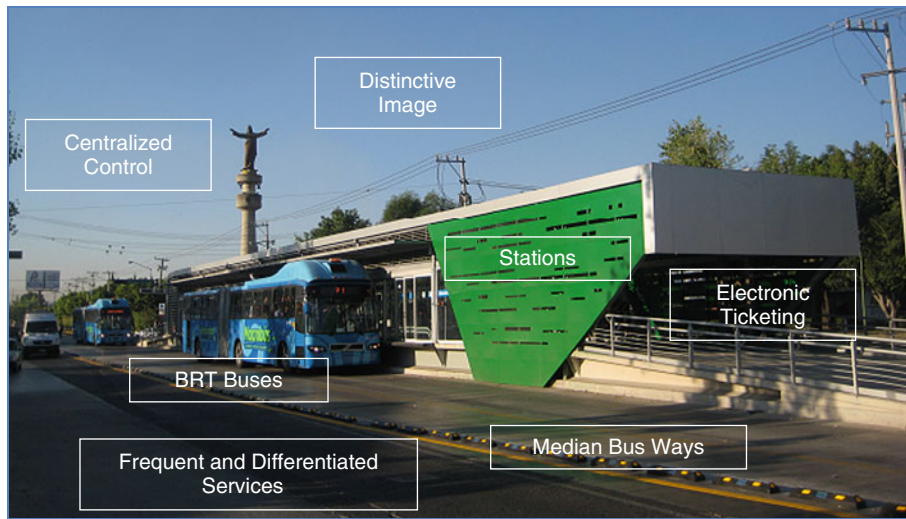
history and current status of BRT in different geographical regions of the world – the United States and Canada, Latin America, Europe, Australia and Oceania, and Asia. The final section indicates future directions.

BRT Components, Characteristics, and Impacts

Components of BRT include [9], running ways, stations, vehicles, fare collection, intelligent transport systems (ITS), service operation plans, and branding elements. There could be different degrees of complexity of each one of these elements, resulting in varied system performance characteristics and system impacts. Performance characteristics include commercial speed, passenger capacity, capital and operational productivity, and costs. Impacts of BRT encompass user perception, travel time, reliability, comfort, and externalities – air pollution, road safety, physical activity, and urban development, among others.

Advanced BRT systems typically involve integration of (see Fig. 1, list adapted from [1, 2, 9]):

- Median running ways for exclusive use of the BRT system buses which are separated from the rest of the traffic through raised curbs (right of way A or B, according to the classification by Vuchic [10]).
- Stations with off-board payment and platforms with level access for boarding to the buses.
- Large buses with multiple doors, special design features, and lower emission levels than conventional buses.
- Use of advanced electronic ticketing systems, such as contactless fare cards, integrated to other applications.
- Several information technology applications for centralized control – such as automatic vehicle location (AVL) and dispatch systems, and improved user information systems – variable message signs in stations and buses to indicate next bus and next station in real time, and provide public announcements; online and personal data appliance providing routing and schedule information, among other applications.
- Combined service plans according to the passenger demand characteristics, including high frequency trunk line services combined with feeder services, as well as accelerated and express bus services.



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure 1
BRT system characteristics (Guadalajara, México, Macrobus BRT system, CTS Mexico 2010)

- Distinctive image differentiating running ways, stations, buses and overall service from other bus services and transit applications in the city.

Few systems encompass all these components. Each component is adapted to the local conditions and the service needs [1], as well as budgetary constraints. As a result, performance characteristics are varied. Table 1 presents the maximum values of some performance indicators observed:

BRT capital costs are in the range of one tenth to one third of comparable rail systems [2, 14]. BRT costs depend on the selection of system components and performance requirements. Figure 2 shows comparison of capital costs for some systems in the developing world; most systems have been built and equipped at a cost between 1 and 5 million USD per kilometer. The higher cost of the Bogotá BRT system reflects the investment to achieve very high peak load (45,000 pphpd) and commercial speed (28 km/h) [8].

Regarding system impacts, most systems have resulted in higher passenger demand than expected [2, 9, 14]; user satisfaction is frequently high [15, 16]; travel times are usually reduced as a result of higher commercial speeds than buses in mixed traffic [2, 8, 9], reliability increased due to the supporting infrastructure and communication technologies [9], and there is documentation on positive impacts for several systems

regarding reduction of crashes, pollutant emissions, and improved urban environments [9, 14, 17, 18]. Concerning comfort, most systems in developing countries use very high occupancy standards and may not be considered comfortable [8]; this is a result of financial restrictions that require most transit operations in developing cities to be self sustainable. As a result, productivity levels need to be very high. Critics of BRT often cite comfort issues when comparing bus systems with rail [7].

BRT Status Around the World

BRT is currently a key component of an effective urban transport policy to address congestion, pollution, and road accidents. A survey of BRT around the world [6] indicates that there are about 118 cities with BRT or bus corridors. The existing BRT and bus corridors as of January 2011 comprise about 280 corridors, 4,300 km, 6,700 stations, and use 30,000 buses, serving about 28 million passengers per day [6]. As of January 2011, about 49 new cities were building BRT systems, 16 cities were expanding their corridors, and 31 cities indicated they were at initial planning stages [6]. What used to be unusual in the early 1990s became common in 2010. Most cities have either developed BRT or bus corridors, or have considered their inclusion in their transportation improvement plans.

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 1 Maximum values for some performance indicators in selected BRT systems

Performance indicator	Definition	Value (year)	System, city (date)	System features
Commercial speed	Distance/time as perceived by the user on board (km/h)	42 km/h (2011)	Metrobüs, Istanbul, Turkey	Fully segregated busway on expressway, stations every 1.1 Km [11]
Peak section load	Passengers/hour/direction (pphpd)	45,000 pphpd (2011)	TransMilenio, Bogotá, Colombia	Median busway, level access stations with five platforms, overtaking lanes and combined services –local, express, seven standees per square meter, dense urban area [12]
Infrastructure productivity	Passengers/kilometer of busway	35,800 (2011)	Guangzhou BRT, China	Median busway, with long station, overtaking lanes, open operation 40 routes, very dense urban area [13]
Capital productivity	Passenger boardings/bus/day	3,100 (2010)	Macrobus, Guadalajara, México	Median busway, overtaking lanes relatively dense, mixed use urban area [8]
Operational productivity	Passenger boardings/bus kilometers	13.2 (2010)	Metrovía, Guayaquil, Ecuador	Median busway, dense urban area, very low fare (USD 0.25 per trip) [8]

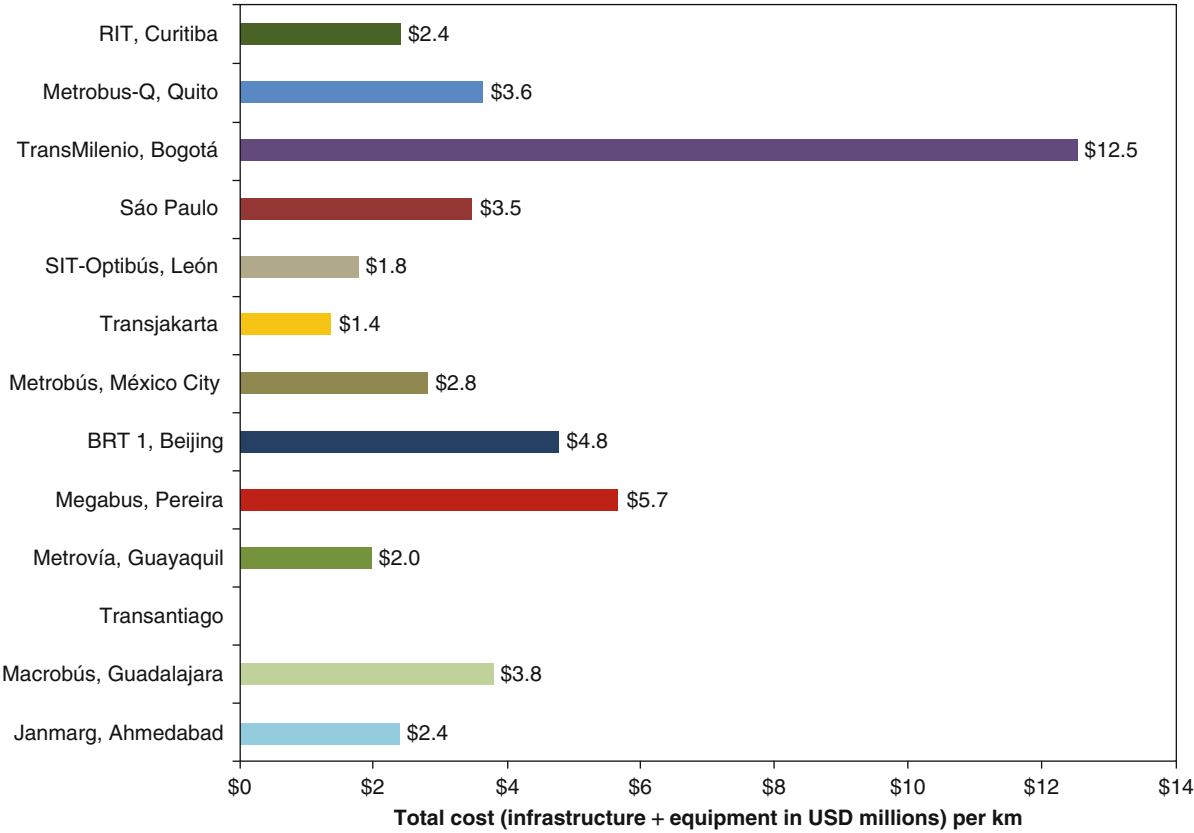
Table 2 presents a regional distribution of BRT and bus corridors around the world, which shows its presence in all continents. Latin America has about one fourth of the cities in the world, but concentrates two thirds of the ridership. There are a very high number of cities and kilometers in Asia, which is the fastest urbanizing region in the world. Usage in Europe, the USA, and Canada is comparatively low in relation with the total kilometers reported. Only two cities in Africa have introduced BRT: Johannesburg, South Africa, and Lagos, Nigeria. The only intercontinental BRT is in Istanbul, Turkey, crossing the Bosphorus Strait.

Figure 3 shows the number of cities introducing BRT or bus corridors since 1970, as well as the total cumulative number of cities. Most cities in the list (97), introduced BRT or bus corridors in the first decade of the twenty-first century. The highest number of cities introducing BRT or bus corridors in the last decade is in China, followed by Indonesia, and the Latin American region.

Some trends are emerging in the BRT Industry:

- Implementation of integrated transit systems based on BRT: The initial phase of implementing isolated corridors is evolving toward citywide systems
- Improved processes for private participation in operations: Most BRT systems in developing countries operate under public–private partnership agreements, using performance-based concession contracts which are awarded either through competitive tendering – with some provisions to include incumbent operators, or direct negotiations of new concessions with existing private providers [8].
- Increased funding from national governments: BRT systems are eligible for funding from the national or federal governments in several countries, like Mexico – through the national fund of infrastructure FONADIN [23]; Brazil – through the Program for Growth Acceleration PAC 2 Mobility in Large Cities [24]; and India – through the Jawaharlal Nehru National Urban Renewal Mission JnNURM [25] and the National Urban Transport Policy [26], among others.
- Growth of bus manufacturers and technology providers: Commercial vehicle manufacturers and

integration, often including other modes of transport like Metro (Sao Paulo [19], Santiago [20], and Guangzhou [13]); Light Rail Transit (Guadalajara [21], Monterrey); and conventional buses (Sao Paulo [19], Santiago [20], and Bogotá [22]).

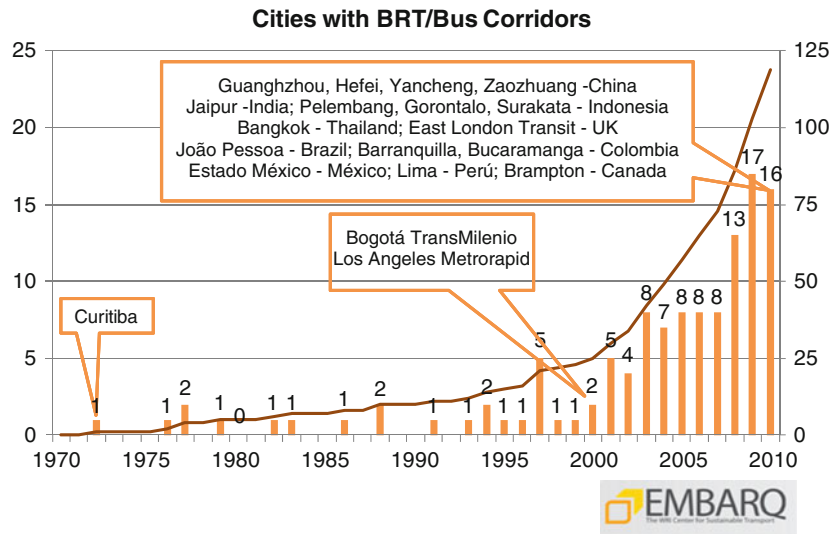


Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 2 Capital costs per kilometer for selected BRT systems (2009) (Source: Hidalgo and Carrigan [8])

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 2 Regional distribution of BRT and bus corridors as of January 2011

	Cities	Corridors	Kilometers	Stations	Buses	Passengers/day
Africa	2	2	47	63	363	290,000
Asia	33	85	1,306	1,658	6,590	6,289,531
Europe	25	32	291	609	781	629,369
Europe/Asia	1	2	43	33	300	700,000
Latin America and the Caribbean	32	90	1,330	2,687	18,656	17,591,945
Oceania	5	12	324	142	1,411	345,800
USA and Canada	20	57	993	1,485	1,993	1,013,901
Total	118	280	4,335	6,676	30,094	26,860,546

Source: EMBARQ BRT/Bus Corridors Database [6]



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 3
Cities with BRT/bus corridors 1970–2010 (Source: EMBARQ BRT/Bus Corridors Database [6])

information technology providers are increasing their activity, especially in emerging economies like Brazil, China, India, and Indonesia.

- Technological developments in vehicles and information systems are also improving the quality, performance, and impact of BRT [9]. Advanced technologies include cleaner fuels – Compressed Natural Gas CNG, Ultra Low Sulfur Diesel ULSD, Biofuels, Hydrogen; improved propulsion technologies – hybrid drive trains, electric; emissions posttreatment – catalytic converters, particulate filters; improved central dispatch and real-time control systems – automatic vehicle location (AVL) and operations control; enhanced fare collection systems using electronic ticketing and contactless fare cards; improved user information systems – variable message signs, communication with personal wireless devices for routing, information of next buses and public announcements, among others.

Despite the growth, there are some outstanding issues:

- BRT does not have a single meaning and image – a broad spectrum of applications, from improved bus service on mixed traffic to totally segregated systems, are considered BRT [1, 2, 9].

- It is often regarded as a “second best” as compared to rail alternatives without a fair evaluation or alternatives analysis [2, 7, 10, 14].
- Its ability to foster urban development and the use of space designated for cars are often questioned, as well as its actual costs and impacts [7].

Several systems in the developing world suffer problems like [8]

- Rushed implementation – several components incomplete at the time of commissioning, but gradual improvement over time has been observed
- Very tight financial planning – user fares are not defined technically generating risks in some systems
- Very high occupancy levels – the adopted standard of 160 passengers/vehicle for articulated buses is not acceptable by the users
- Early deterioration of infrastructure – lack of road surface reinforcement or problems in design and construction result in maintenance issues
- Delayed Implementation of fare collection systems, which often require longer timetables than initially expected and need very tight supervision
- Insufficient user education for initial implementation and system changes

These issues are often the result of poor planning, implementation, and operation, due to financial, institutional, and regulatory constraints; they are not intrinsic to the BRT concept [8].

BRT in the United States and Canada

According to Levinson et al. [3], the idea of using buses to provide mass transit is not new. Plans for bus systems, displaying the current understanding of BRT, were proposed as early as 1937, when a “plan called for converting three west side rail rapid-transit lines to express bus operation on super highways with on-street distribution in central areas and downtown,” in Chicago. Similar major initiatives for buses on reserved lanes on freeways were proposed in a 1956–1959 Washington D.C. Plan, a 1959 St. Louis Plan, and a 1970 Milwaukee Plan [3].

Several research studies, indicating the potential of BRT and suggesting guidelines for the design of bus facilities were completed between 1966 and 1975. Levinson et al. [3] indicate that “most of these planning studies focused on the facility aspects of BRT, often as an adjunct to urban freeways. Little or no attention was given to the station, service, and image/identity aspects of BRT.”

The planning emphasis changed in the late 1970s, from bus use of streets and highways toward the provision of high-occupancy vehicle (HOV) lanes and light rail transit (LRT) due to environmental and performance considerations [3]. LRT tended to be considered more fully in alternative analyses, due to lack of information on the potential benefits and costs of BRT [3]. More recently, BRT recaptured interest of planners and funding agencies [3]. The Federal Transit Administration (FTA) sponsored a BRT conference in 1998, using Curitiba’s BRT system as a model, published major documents highlighting BRT, established a BRT Consortium with 17 supporting cities in 1999, and launched a BRT “Demonstration Program” involving 15 cities [3].

The most important BRT systems and bus corridors in the United States and Canada by January 2011 are presented in Table 3, including date of initial implementation, some features, and estimated ridership. There are 20 cities, featuring 57 corridors and 993 km, serving about 1,013,901 passengers per weekday.

Systems in the United States are not usually displaying full BRT features. The most advanced applications are the Orange Line (Los Angeles, California, 2007, Fig. 4), EmX (Eugene, Oregon, 2008), and the HealthLine (Cleveland, Ohio, 2009). Evaluations of these and other applications in the United States are available in the FTA document “Characteristics of BRT for Decision Makers” [9] and the National BRT Institute [27], a federal funded program.

In Canada, the City of Ottawa, implemented a very interesting concept, the Transitway, a fully segregated corridor with services coming in and out, allowing for direct trips without transfers [9, 28]. Plans to partially replace the Transitway system with Light Rail are underway [29]. The suburban communities of York (2005) and Brampton (2010), in Ontario, also improved transit using BRT.

BRT in Latin America

Many Latin American cities have embraced bus rapid transit as a key component of their transit systems. Curitiba, Brazil, can be considered the cradle of modern BRT [5]. Since the 1970s, Curitiba’s administrators have introduced constant innovations to the city’s bus-based transit system. Originally, the bus system evolved from conventional buses in mixed traffic to busways, which were fitted with at-level boarding, prepayment, and articulated buses, creating the first full BRT system in the world in 1982 [5]. Later on, the city introduced high capacity bi-articulated buses and the electronic fare ticketing systems.

In 2009, the Curitiba integrated bus system was upgraded, again, with the introduction of the Green Line, its sixth BRT corridor which includes the operation of 100% bio-diesel articulated buses [5]. In 2010, the city also introduced capacity enhancements for one of its existing corridors (Fig. 5). Capacity expansions are underway in all the original corridors.

The success story of Curitiba has been replicated in several cities through the region, with adaptation to the local conditions [34]. Quito replicated the Curitiba concept in 1995, with the use of electric trolleybuses to preserve the environment in its historic downtown [34]. Bogotá, expanded the concept in 2000, using very large stations with passing lanes, combined local and express services, electronic ticketing system and

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 3 Most relevant BRT systems and bus corridors in the United States and Canada by January 2011

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day (year)	Source
Pittsburgh, Pennsylvania	1977	South, MLK East, West Busways	3	31.3	50	103	51,700 (2009)	[6, 9]
Ottawa, Ottawa	1983	Transitway	3	30.0	37	195	97,739 (2008)	[6, 9]
Miami, Florida	1997	South Miami-Dade Busway	1	34.0	30	46	23,000 (2009)	[6, 9]
Orlando, Florida	1997	LYNX Lymmo	1	5.1	22	9	4,475 (2009)	[6, 9]
Chicago, Illinois	1998	Express	3	62.4	154	109	54,742 (2009)	[6, 9]
Los Angeles, California	2000	Metrorapid	21	390.2	650	893	464,600 (2009)	[6, 9]
Oakland, California	2003	San Pablo Rapid	1	23.8	52	26	13,000 (2009)	[6, 9]
Albuquerque, New Mexico	2004	Rapid Ride	1	23.5	30	25	12,430 (2009)	[6, 9]
Boston, Massachusetts	2004	Silver Line	2	11.7	61	62	30,874 (2009)	[6, 9]
Las Vegas, Nevada	2004	MAX	1	12.75	22	20	10,000 (2009)	[6, 9]
Halifax, Nova Scotia	2005	Metrolink	3	39.4	16	15	7,266 (2008)	[6, 9]
York, Ontario	2005	VIVA	5	63.6	59	71	35,300 (2008)	[6, 9, 30]
Los Angeles, California	2007	Orange Line	1	24.65	28	125	62,597 (2009)	[6, 9]
Eugene, Oregon	2008	EmX	1	6.8	18	13	6,200 (2009)	[6, 9]
Phoenix, Arizona	2008	LINK	4	128.0	92	5	2,372 (2009)	[6, 9]
Cleveland, Ohio	2009	HealthLine	1	12.1	36	21	10,591 (2009)	[6, 9]
Kansas City, Kansas	2009	MAX	1	10.2	42	9	4,450 (2009)	[6, 9]
New York, New York	2009	Bx Select Bus	2	26.4	52.7	220	110,187 (2010)	[6, 31]
Snohomish County, Washington	2009	Swift	1	28.9	16	10	4,878 (2010)	[6, 32]
Brampton, Ontario	2010	Züm	1	28.5	17	15	7,500 (2010)	[6, 33]

centralized control, achieving extremely high peak loads – over 45,000 passengers per hour per direction (Fig. 6) [35].

The Curitiba, Quito, and Bogotá successes were then replicated, with adaptations, to at least 29 cities (Table 4). As of January 2011, there were at least 91 BRT and bus corridors; 1,300 km; 2,700 stations; and 18,000 buses, serving more than 17 million passengers per day [6]. Latin America has one fourth of the world cities

with BRT or bus corridors, serving two thirds of the estimated global ridership [6].

Many other cities in the region, like Buenos Aires, Medellin, Cartagena, Cúcuta, Arequipa, Asunción, Chihuahua, Querétaro, San Juan, and Panamá City, were building corridors or in final planning stages as of January 2011 [6].

The highest concentration of BRT and bus corridors is in Brazil with 16 cities and 828 km [6]. It is important



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 4
Orange Line, Los Angeles, North Hollywood station (Source: Gary Leonard, http://www.metro.net/press/2005/10_october/metro_160a.htm#North)



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 5
Boqueirao busway in Curitiba integrated system after capacity expansion in 2010 (Source: Municipality of Curitiba 2010)



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 6

Bogotá TransMilenio BRT system peak section in Avenida Caracas – station with five platforms, prepayment, level boarding and overtaking lanes for local and express services (Source: TRANSMILENIO S.A. 2001)

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 4 Most relevant BRT systems and bus corridors in Latin America and the Caribbean by January 2011

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/ day (year)	Source
Curitiba, Brazil	1972	Rede Integrada de Transporte	6	72	376	2,200	2,260,000 (2010)	[5, 6]
Goiania, Brazil	1976	Rede Metropolitana de Transporte Coletivo	3	35	70	200	200,000 (2010)	[6, 36]
Porto Alegre, Brazil	1977	Prioridade Transporte Colectivo	10	57.2	103	1,300	1,170,000 (2010)	[6, 36]
Sao Paulo, Brazil	1979	Prioridade Transporte Colectivo	10	301.3	602.6	7,604	6,843,664 (2010)	[6, 36]
Juiz de Fora, Brazil	1982	Av. Visconde do Rio Branco	1	5	10	83	75,000 (2010)	[6, 36]
Campinas, Brazil	1988	Prioridade Transporte Colectivo	3	13.4	9	178	160,000 (2010)	[6, 36]
Mauá – Diadema, Brazil	1988	Corredor Metropolitano ABD	1	33	66	233	273,000 (2010)	[6, 36]
Campo Grande, Brazil	1991	Sistema Integrado de Transportes	1	3.2	6.4	89	80,000 (2010)	[6, 36]

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 4 (Continued)

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day (year)	Source
Fortaleza, Brazil	1994	Sistema Integrado de Transportes	1	3.6	7.2	86	77,000 (2010)	[6, 36]
Quito, Ecuador	1995	Metrobus-Q	3	42.2	82	531	440,000 (2010)	[6, 8]
Uberlândia, Brazil	1997	Sistema Integrado de Transportes de Uberlândia	1	17	13	78	70,000 (2010)	[6, 36]
Bogota, Colombia	2000	TransMilenio	7	84	144	1,769	1,700,000 (2010)	[6, 37]
Natal, Brazil	2001	Sistema Integrado de Transportes	2	5	19	200	180,000 (2010)	[6, 36]
Leon, Guanajuato, México	2003	Optibus	4	31	61	90	700,000 (2010)	[6]
Monterrey, México	2003	Metrobus	3	101	201	85	125,281 (2010)	[6]
Belo Horizonte, Brazil	2004	Prioridade Transporte Colectivo	2	23.7	47.4	483	435,000 (2010)	[6, 36]
Feira de Santana, Brazil	2005	Sistema Integrado de Transportes	2	3.5	7	83	75,000 (2010)	[6, 36]
Mexico City	2005	Metrobus	3	67	108	275	620,000 (2011)	[6]
Salvador, Brazil	2005	Sistema de Transporte Coletivo por Ônibus	2	4	8	167	150,000 (2010)	[6, 36]
Guayaquil, Ecuador	2006	Metrovia	2	63	60	215	300,000 (2010)	[6, 38]
Guatemala City	2007	Transmetro	2	35.0	70	400	400,000 (2010)	[6]
Merida, Venezuela	2007	Transmerida	2	30	34	8	8,000 (2010)	[6, 39]
Pereira, Colombia	2007	Megabus	3	19.15	37	137	115,000 (2010)	[6, 40]
Recife, Brazil	2007	Sistema Estrutural Integrado (L-O)	1	9	28	444	400,000 (2009)	[6, 41]
Santiago, Chile	2008	Transantiago	3	26	52	130	130,000 (2010)	[6]
Cali, Colombia	2009	MIO	6	179.0	358	470	215,000 (2010)	[6, 40]
Guadalajara, Mexico	2009	Macrobus	1	16	27	144	130,000 (2010)	[6]
Barranquilla, Colombia	2010	Transmetro	1	13.4	15	92	32,000 (2010)	[6, 40]

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 4 (Continued)

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day (year)	Source
Bucaramanga, Colombia	2010	Metrolinea	1	8.9	24	131	75,000 (2010)	[6, 40]
Estado Mexico	2010	Mexibus	1	16	32	63	63,000 (2010)	[6, 42]
João Pessoa, Brazil	2010	Corredor de Ônibus de João Pessoa	1	2.5	5	111	100,000 (2010)	[6, 43]
Lima, Perú	2010	Metropolitano	2	27	35	627	160,000 (2010)	[6, 44]



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 7
Expresso Tiradentes, Sao Paulo, Brazil (Source: Sao Paulo Transportes SPTrans 2008)

to indicate that most cities in Brazil, outside Curitiba and Goiania, keep the general model of busways, rather than full BRT systems. There was a major upgrade of the integrated system in Sao Paulo in 2005 [19], which included the introduction of an elevated fully segregated busway – Expresso Tiradentes (Fig. 7). Similarly, Santiago, Chile introduced a major reform in bus services in 2008, which includes several busways,

and prepayment in selected stations, but keeps most fare collection off board and has few segregated busways [20].

BRT in Europe

European cities have preserved and enhanced their transit systems in high capacity corridors using metros and tramways mainly, with buses only considered in

medium capacity corridors. Heddebaut et al. [45] consider that high capacity BRT configurations do not suit the European context (lack of available space, undesirable urban cuttings, and low demand). These authors prefer the term “Bus with a High Level of Service (BHLS),” rather than BRT, to refer to the European applications introduced in several cities (Table 5). Most applications have bus lanes in congested areas (downtown), sharing the road with taxis and bicycles, and in few cases lanes in expressway (High-occupancy vehicle lanes in Madrid and Grenoble, Metrobüs in Istanbul).

Case studies compiled by the European Union project COST [46] indicate that BHLS corridors are well adapted to new urban zones, small towns, and medium-sized conurbations [45]. They also allow for a variety of configurations (feeder-trunk and direct services), and permit transformation into tramway systems once there is sufficient demand. Some applications used advanced vehicles, including optical or magnetic or physical guidance (e.g., Castellón de la Plana, Eindhoven, Leeds).

Outside the European Union, the most widely used application is the Istanbul Metrobüs, which connects Europe and Asia in the only intercontinental BRT system (Fig. 8). This system has central busways on expressway (fully segregated BRT), very long platforms, low floor buses (articulated and bi-articulated), and achieves very high commercial speed (42 km/h) and peak throughput (30,000 passengers/hour/direction) [11]. It carries 700,000 passengers per day in a 45 km corridor, under expansion in 2011.

Table 5 shows the most relevant corridors in Europe, including Turkey. There are at least 27 cities in Europe with bus corridors, 35 corridors, 335 km, and 1,083 buses, serving 1.3 million passengers per day (53% in Istanbul) [6].

BRT in Asia

BRT is evolving very rapidly in several Asian countries, such as China [49], Indonesia [50], India [51], and Iran [6]. Applications are very varied, from very basic bus corridors (e.g., Delhi and Pune) to very complete systems (e.g., Ahmedabad and Teheran). Table 6 lists the most relevant corridors as of January 2010.

There are at least 33 cities, with 85 corridors, 1,306 km, 1,720 stations, 6,590 buses, serving 6.3 million passengers per day. Forty-five percent of the cities started operation in 2009 and 2010 and many other cities are building and planning BRT and bus corridors across the region.

One important advance in BRT development is the application in Guangzhou, China (Fig. 9), which uses direct services, with large stations, overtaking lanes and the use of advanced technologies for control and user information [49]. This system features very high throughput (30,000 passengers per hour per direction), with small number of transfers.

BRT in Australia and New Zealand

Australia has a long tradition on BRT, as one of the first world systems, the Adelaide North East Busway started operation in 1986 [55]. Brisbane, Melbourne, Sydney, and Auckland introduced bus corridors between 2001 and 2005 (Table 7). Bus corridors in Australia and New Zealand have very diverse design features, from guided busways (Adelaide) and fully grade-separated bus-only roads (Brisbane, sections of Sydney), to on-street busways (Auckland) and bus lanes (Melbourne) [55].

According to Currie and Delbosc [55], the BRT concept continues to be very attractive in the region with rapid increase in kilometers and ridership, especially on established systems. The authors identify risks in the provision of vehicles and accommodating high patronage growth, but highlight the relative cost-effectiveness. BRT development in Australia and New Zealand has exceeded rail in the last decade; nevertheless, rail has received greater attention lately [55].

Brisbane (Fig. 10), exhibits very advanced design features, and recently completed a downtown tunnel.

BRT in Africa

Infrastructure and service development in African cities is beginning to pick up attention by the local authorities, as urbanization and GDP increase. Governments are beginning to recognize the need for organized transit, to replace low-quality informal paratransit services [56].

Two cities, Lagos, Nigeria, and Johannesburg, South Africa, started operations of BRT systems in 2009. Lagos implemented a corridor on the parallel

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 5 Most relevant bus corridors in Europe as of January 2010, including Istanbul, which extends to Asia

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day (year)	Source
Paris, France	1993	TVM	1	19.5	29	33	65,000 (2009)	[6, 47]
Ipswich, UK	1994	Ipswich Rapid Transit	1	0.5	1	1	739 (2010)	[6]
Leeds, UK	1995	Superbus	2	4.2	8.4	62	31,000 (2005)	[6, 48]
Dublin, Ireland	1997	QBC	1	8.4	17	68	34,000 (2009)	[6, 46]
Rouen, France	2001	TEOR	3	13	52	64	45,000 (2009)	[6, 47]
Utrecht, The Netherlands	2001	TVM	2	8.2	16	42	33,500 (2005)	[6]
Caen, France	2002	Twisto TVR	1	15.7	34	24	48,000 (2009)	[6, 47]
Nancy, France	2002	TVR (GLT)	1	8	30	18	37,000 (2009)	[6, 47]
Amsterdam, The Netherlands	2002	Zuidtangent BRT	1	33	66	80	40,000 (2009)	[6, 46]
Bradford, UK	2002	Manchester Road	1	3.7	7.4	7	5,467 (2005)	[6, 48]
Eindhoven, The Netherlands	2003	Phileas	1	15	30	12	28,500 (2009)	[6, 9]
Crawley, UK	2003	Fastway	2	24	48	23	6,000 (2005)	[6, 46]
Prato, Italy	2004	LAM	1	15	30	120	60,000 (2009)	[6, 46]
Edinburgh, Scotland	2004	Fastlink	2	5	10	55	44,000 (2005)	[6, 48]
Lyon, France	2006	C-Lines	1	4	10	5	4,700 (2009)	[6, 47]
Nantes, France	2006	BusWay (Line 4)	1	7	15	20	21,000 (2009)	[6, 47]
Kent, UK	2006	Fastrack	1	15	30	14	5,726 (2005)	[6, 48]
Luton, UK	2006	FTR train to plane	1	5	2	4	30,000 (2010)	[6]
York, UK	2006	FTR First York	1	5	10	11	5,500 (2010)	[6]
Lorient Triskell, France	2007	BHLS	1	5	15	13	15,000 (2009)	[6, 47]
Maubeuge, France	2008	BHLS - Viavil	1	7.5	14	20	5,000 (2009)	[6, 47]
Toulouse, France	2008	Toulouse BSP	2	11	17	11	13,300 (2009)	[6, 47]
Istanbul, Turkey	2008	Metrobus	2	43	33	300	700,000 (2010)	[6, 11]
Castellon de la Plana, Spain	2009	TVRCAS	1	1	4	2	4,000 (2010)	[6]
Cambridge, UK	2009	Guided Busway	1	25	50	46	36,938 (2005)	[6, 48]
Swansea, UK	2009	FTMetro	1	13.5	27	10	5,000 (2010)	[6]
London, UK	2010	East London Transit	1	20	40	18	9,000 (2010)	[6]



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 8
Istanbul Metrobüs, intercontinental BRT system (Source: Dario Hidalgo, EMBARQ, March 2010)

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 6 BRT and bus corridors in Asia as of January 2010

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day (year)	Source
Taipei, China Taiwan	1996	Busways	10	30.3	143	1,680	1,680,000 (2008)	[6, 52]
Kunming, China	1999	Busways	5	46.7	63	156	156,000 (2010)	[6, 53]
Nagoya, Japan	2001	Yutorito Line	1	6.5	9	52	26,000 (2010)	[6]
Seoul, North Korea	2003	Median bus lanes	5	43	73	500	400,000 (2009)	[6, 53]
Jakarta, Indonesia	2004	TransJakarta	10	172.2	241	520	276,643 (2010)	[6, 50]
Beijing, China	2005	Beijing BRT	3	34.5	60	200	200,000 (2008)	[6, 53]
Batam, Indonesia	2005	Bus Pilot Project	2	36	20	22	1,472 (2010)	[6, 50]
Hangzhou, China	2006	Hangzhou BRT	2	18.8	50	104	153,000 (2010)	[6, 53]
Pune, India	2006	Pune BRTS	2	16.5	33	54	54,000 (2010)	[6]
Bogor, Indonesia	2007	Trans Pakuan	2	60	56	30	2,978 (2010)	[6, 50]

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 6 (Continued)

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day (year)	Source
Tehran, Iran	2007	Tehran BRT	5	91	114	1,125	1,440,000	[6]
Changzhou, China	2008	Changzhou BRT	2	41	51	240	240,000 (2010)	[6, 53]
Chongqing, China	2008	Chongqing BRT	1	6	9	10	1,500 (2010)	[6, 53]
Dalian, China	2008	Dalian BRT	1	9	13	87	87,000 (2010)	[6, 53]
Jinan, China	2008	Jinan BRT	4	34.4	46	165	162,750 (2010)	[6, 53]
Xiamen, China	2008	Xiamen BRT	3	48.9	40	177	177,750 (2010)	[6, 53]
New Delhi, India	2008	Delhi BRTS	1	5.8	9	96	95,565 (2010)	[6]
Yogyakarta, Indonesia	2008	Trans Jogja	3	90	76	75	12,702 (2010)	[6, 50]
Zhengzhou, China	2009	Zhengzhou BRT	1	26.6	38	170	84,000 (2010)	[6, 53]
Ahmedabad, India	2009	Janmarg	3	39	61	60	102,013 (2010)	[6, 54]
Bandung, Indonesia	2009	Trans Metro Bandung	1	16	15	10	589 (2010)	[6, 50]
Manado, Indonesia	2009	Trans Kawanua	2	51	39	27	108 (2010)	[6, 50]
Pekanbaru, Indonesia	2009	Trans Metro Pekanbaru	2	74	58	20	5,691 (2010)	[6, 50]
Semarang, Indonesia	2009	Trans Semarang	1	30	53	20	2,560 (2010)	[6, 50]
Guangzhou, China	2010	Guangzhou BRT	1	22.5	26	800	800,000 (2010)	[6, 53]
Hefei, China	2010	Hefei BRT	2	12.7	14	65	65,250 (2010)	[6, 53]
Yancheng, China	2010	Yancheng BRT	1	8	21	20	20,000 (2010)	[6, 53]
Zaozhuang, China	2010	Zaozhuang BRT	1	33	24	20	20,000 (2010)	[6, 53]
Jaipur, India	2010	Jaipur bus	1	7.1	10	20	6,200 (2010)	[6]
Gorontalo, Indonesia	2010	Trans Hulonthanlangi	3	90	84	15	1,920 (2010)	[6, 50]
Palembang, Indonesia	2010	Trans Musi	2	60	106	15	1,920 (2010)	[6, 50]
Surakarta, Indonesia	2010	Batik Solo Trans	1	30	53	15	1,920 (2010)	[6, 50]
Bangkok, Thailand	2010	Bangkok BRT	1	15.9	12	20	10,000 (2010)	[6, 53]



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 9
Guangzhou, China, BRT corridor (Source: Karl Fjellstrom [49] <http://www.transportphoto.net/photo.aspx?id=7599&c=Guangzhou&l=en>)

Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Table 7 BRT and bus corridors in Australia and Oceania as of January 2010

City	Initial year	Name	Corridors	Kilometers	Stations	Buses	Passengers/day	Source
Adelaide, Australia	1986	O-Bahn	1	12	3	138	28,000 (2009)	[6, 55]
Brisbane, Australia	2001	Brisbane Busway	3	23.8	21	1,002	242,000 (2009)	[6, 55]
Melbourne, Australia	2003	SmartBus	4	233	56	122	36,200 (2009)	[6, 55]
Sydney, Australia	2003	Busways	3	49.1	58	140	32,400 (2009)	[6, 55]
Auckland, New Zealand	2005	Northern Busway	1	5.9	4	9	7,200 (2009)	[6, 55]

roads of an existing expressway with a length of 22 km, 26 stations, and 220 buses, carrying 220,000 passengers per day [57]. However, it is not considered a full BRT, as the bus lanes are on the kerb side, with some sections on mixed traffic and access to the buses requires stairs [56].

Johannesburg launched a full BRT system in preparation to the Football World Cup in 2009 (Fig. 11). The system is 25 km long (out of 122 km planned), with 33 stations and 143 buses. It connects the high-density community of Soweto with the central business district and carries 70,000 passengers per day [58].



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 10
Brisbane BRT (Source: Karl Fjelstrom December 2004, <http://www.transportphoto.net/photo.aspx?id=1303&c=Brisbane&l=en>)



Bus Rapid Transit: Worldwide History of Development, Key Systems and Policy Issues. Figure. 11
Rea Vaya, Johannesburg's BRT, South Africa (Source: Rea Vaya (2010) <http://www.reavaya.org.za/photo-gallery/state-of-the-art/category/1>)

Cape Town (South Africa) started operations of its BRT in 2011. There are systems in intermediate planning stages in Port Elizabeth and Pretoria (South Africa); Dar es Salaam (Tanzania) and Accra (Ghana) [56]. Other cities considering BRT include Kampala (Uganda), Nairobi (Kenya), and Bloemfontein – Ethekwini, East London – Buffalo City, Ekurhuleni, Polokwane, and Rustenburg (South Africa) [56].

The main challenges for African cities are the creation of local capacity to oversight and operate systems, transforming the paratransit informal services and funding the capital costs (infrastructure and buses) [56].

Future Directions

BRT will evolve in several directions, namely:

1. BRT will gradually become an integral part of most transit systems, as the cities grow their corridors into networks and integrate BRT services with other modes of transport (metro, regional rail, and standard buses). Pedestrian and bicycle access will be improved, and bike- and car-sharing services will be incorporated around BRT stations.
2. Automatic guidance systems, using video, magnetic or physical devices, will evolve to ensure optimal docking at stations. In some cases, priority lanes will be intermittent; only a few meters ahead and behind the bus will be reserved using advanced signal and communications technologies, at other times the lanes may be used for general traffic [59]. This will eliminate the perception of “empty lane” in systems with headways beyond 2 min.
3. The buses will have several advanced technology components: hybrid buses, plug-in hybrids, or fully electric with high autonomy or extra-fast battery charging systems at each station. Alternative technologies will evolve, such as solar recharging hydrogen fuel cell, biofuels from sustainable feedstock, among others.
4. Programming and operations will improve due to the availability of intelligent transport systems (ITS), including the integration into the signal networks (advanced transit signal priority [TSP]). Improved control (Global Positioning System [GPS], Automatic Vehicle Location [AVL], and Operations Support Systems) will

allow optimal regulation and dynamic equilibrium of the supply (buses) and the travel demand (passengers). Very advanced routing systems will be possible, including super express, express, and local, services, as well as direct services, to reduce transfers.

5. Fare collection systems will be integrated into cell phones and turnstiles will no longer be required. Tickets will be deducted automatically from electronic wallets, which will have other multiple applications, just as debit cards. User fares will be differentiated by time of day, day of week, and length according to the supply and demand conditions of the system, increasing efficiency and service quality.
6. User information systems will be dynamic, with electronic panels that indicate the next bus and public announcements, helping users to navigate the system in advanced screens or cell phones.
7. Land use along the corridors will include good accessibility, high-density, and mixed uses (Transit-Oriented Development [TOD]). BRT will support urban development and vice versa.
8. Contracts with private operators will be based on performance, with dynamic adjustment formulas of their revenue according to changes in input costs.
9. Infrastructure, technology, training, education, and control will ensure safety, with a vision of zero tolerance of severe injuries and fatalities.
10. BRT will facilitate physical activity, low or zero emissions, and universal accessibility (disabled people).

Many of these advances are already applied in several systems around the globe or under research and development. Integration into future BRT systems will happen in the next few years.

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Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects

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Article Outline

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Glossary

Access time The component of door-to-door travel time spent leaving the point of trip origin to a transit stop.

Annualized operating cost The direct cost of operating and maintaining a transit route or set of routes over a whole year; an average value.

Articulated bus A bus vehicle with three (exceptionally four) axles and two (exceptionally three) body sections connected by body joints that provide a continuous interior for passengers. Body articulations allow the bus to make turns occupying a moderately wider body profile than a regular, two-axle bus.

At-grade BRT Bus rapid transit that is predominantly on ROW B and has most of the following elements: signal priority at intersections and other preferential treatments elsewhere; well-spaced stops like stations, with good passenger amenities; regular, reliable services throughout the day; off-board fare collection; real-time arrival information; large, distinctive buses allowing rapid passenger exchange; and a clear, branded image.

Automated guided transit (AGT) Automated vehicles, operated on ROW A, in either a shuttle or loop configuration, typically serving internal circulation needs of large institutions or downtowns. Vehicles may be either steel wheel or rubber tired.

Average operating speed A performance indicator computed by dividing the length of a route or line by the travel time required.

Bogie or truck (United States) Frame containing axle, motor, and brake assemblies and pivots under the body/chassis of a rail vehicle.

Build-operate-transfer (BOT) A project implementation method where one single entity is responsible for building transit infrastructure, procuring all needed equipment and managing the operations for an initial period time before the eventual hand-over to public ownership.

Bus lane Traffic lane for exclusive (or dominant) use by buses. It may be:

Contraflow – Operating in the opposite direction from other traffic.

Exclusive – Physically separated lanes (usually two) for bus use only.

High Occupancy Vehicle (HOV) Lane – A traffic lane open only to vehicles with more than a minimum number of persons onboard.

Regular – Lane on urban street or motorway reserved only for buses, separated by markings, signs, or cones but not physically separated.

Bus rapid transit (BRT) or bus transit with high level of service (BHLS) Bus transit system with mostly ROW B, long spacings between stops, signal priorities, vehicles with distinct image, and other rail-like components for high performance.

Bus transit system (BTS) A bus service designed as a coordinated system with average stop spacings of at least 300 m, some bus lanes, passenger-friendly vehicle design, operations control, passenger information, etc., for higher speed, reliability, and efficiency.

Consist A set of rail vehicles coupled into a train.

Cross-subsidization The concept of using excess revenues (profits) from one line or route and using them to support another line that earns revenues less than its costs.

Deadheading Moving a transit unit to a line from a depot or storage location or repositioning a vehicle to another line without passengers.

Design-build model An approach to major projects making the same firm/consortium responsible for both the design and construction phases.

Design-build-operate-maintain (DBOM) model An approach to major projects in which the same firm/consortium is responsible for the design, construction, operation, and maintenance phases.

Diametrical line (or route) A transit line that has a radial alignment from a suburb to center city, crosses it, and continues into another suburb.

Economy of scale The unit cost of output decreases with the quantity of output.

Elasticity of demand The percentage change in ridership over the percentage change in some other quantity (e.g., fare or frequency)

Frequency The rate at which transit units pass a fixed point, usually expressed per hour; it is the inverse of headway but usually expressed in minutes.

Global positioning system (GPS) The currently dominant vehicle location system, based on taking position fixes from multiple satellites.

Guideway A travel way (rail track, guide beam, and other guiding surfaces) that physically guide vehicles. Guideways for nonrail vehicles always require ROW A.

Headway The time interval between transit units passing a fixed point, usually expressed in minutes. It is

the inverse of frequency, which is usually expressed as departures per hour.

High occupancy vehicle (HOV) lane A traffic lane open only to vehicles with more than a minimum number of persons onboard.

Hybrid vehicle A bus or rail transit vehicle that combines two different forms of propulsion like an internal combustion engine and an electric motor, which operate in optimum combination for each regime, such as in acceleration, low or high speed, etc.

Intelligent transportation system (ITS) A package of hardware and software specifically designed for improving transportation operations, information to the public, and/or information for service planning.

Interlining The practice of having a vehicle continue onto another line or route rather than reversing at a terminus.

Level of service (LOS) The combined service characteristics experienced by the user.

Light rail transit (LRT) A transit mode utilizing predominantly ROW B, sometimes A or C, on different network sections. Its electrically powered vehicles operate in one- to four-car transit units. The mode has a wide range of LOS and performance characteristics.

Light rail vehicle (LRV) An electric rail transit vehicle, powered or unpowered, with up to seven body sections and overall length of 20–50 m capable of operating on ROW A, B, and C.

Line capacity The maximum throughput of transit units (TUs) or spaces measured at one point on a line on a per-unit time basis; it has a wide range of values depending upon safety regime and assumed crowding standards.

Linked trip A trip that includes all segments a user makes on public transport vehicles.

Load factor or coefficient of utilization Ratio of passengers in a vehicle/transit unit and its total capacity in spaces.

Locally preferred alternative The project alternative selected locally that is then submitted to the federal government for further review and a funding decision (specific to the United States).

Marginal cost The cost to carry one more vehicle on a roadway, one more person in a transit vehicle, or,

in general, the cost of providing one more unit of service output.

Maximum load section (MLS) The segment of a line or route on which the maximum number of passengers is carried.

Metropolitan planning organization (MPO) A governmental body legally required to do transportation forecasting and to propose a transportation improvement/investment plan for a metropolitan region (specific to the United States).

Modal split The fraction of trips by a particular mode along a route or line, between two points, or across an entire region.

Monorail An urban transit technology that operates exclusively on right-of-way A using in most cases tires for both lateral and vertical support on a beam with a special cross section, typically a proprietary design.

National Transit Database (NTD) A source of operating statistics and cost information for each transit agency receiving federal funds that is broken into categories used for cost modeling and estimating (United States only).

No-build scenario A project alternative used to compare what may happen if no action is taken. The no-build alternative may sometimes include modest Transportation Systems Management investments.

O-Bahn Bus transit technology in which buses have two horizontal wheels and roadway has two lateral surfaces; the buses can operate on regular streets or enter sections where guiding wheels stretch out and provide guidance against the lateral surfaces so that the driver does not steer.

Operating speed Average speed on a line or network including times for stops, but not terminal times and deadheading.

Opportunity cost The forgone possibilities when resources are committed to a particular project alternative.

Pantograph A spring-loaded mechanism mounted atop electric vehicles that glides along and collects current from a suspended high-voltage catenary.

Paratransit In the narrow definition, services provided as a public service on a demand-responsive basis; in the broader definition any for-hire services that are not fixed route (e.g., taxis, jitneys, vanpools, airport shuttles, etc.).

People mover The informal name for Automated Guided Transit (AGT) system.

Public-private partnership (PPP) A method of project development in which responsibilities and finances are divided amongst various parties in recognition of the benefits each can receive, hopefully to the mutual benefit of all parties.

Radial line (or route) A line or route that begins in CBD or at a center of activity and goes to suburbs, in the direction of lower demand density.

Real-time passenger information (RTPI) The estimated arrival time for a vehicle at a particular stop based on tracking of actual location versus scheduled location; it can be delivered with signs in the field over the Internet, over Personal Digital Assistants (PDAs), cell phones, etc.

Regular Lane on urban street or motorway reserved only for buses, separated by markings, signs, or cones but not physically separated.

Right-of-way (ROW) Broadly speaking, any path or way on which a transit vehicle travels. Transit rights-of-way (ROW) are classified in three categories:

Category A Right-of-Way (ROW A) – Fully controlled ROW without (or with fully protected) grade crossings or any legal access by other vehicles or persons; also called “grade-separated” or “exclusive” ROW. It can be a tunnel, aerial, or at-grade level.

Category B Right-of-Way (ROW B) – ROW horizontally separated from other traffic (by curbs, barriers, grade-separations, etc.), but with grade crossings for vehicles and pedestrians usually at regular street intersections.

Category C Right-of-Way (ROW C) – Surface streets with mixed traffic. Transit may have preferential treatment, such as reserved lane but not physically separated lanes, or it may travel in general traffic lanes.

Short turning Transit line on which some transit units turn back at a station closer than the outlying terminal.

Shuttle A route that consists of only two stops, one at each terminus.

Space-averaged load factor A performance indicator used to measure vehicle space consumption efficiency over the length of a route, computed as the

ratio of total space-distance consumed over total space-distance offered.

Streetcar A rail transit mode consisting of electrically powered rail vehicles operating in one- to three-car transit units, usually on ROW B or C.

Sustainable Development The concept that economic development should take place so that nonrenewable resources are not depleted and natural systems of restoration and pollution mitigation are not overloaded.

Tangential route (or Line) A route or line that does not enter into a central area, but instead connects peripheral locations, generally having the property of more even loading because demand does not increase continually as with radial routes.

Timed-transfer system (TTS) A network consisting of transit lines and one or several transit centers or focal points at which transit units from intersecting lines arrive simultaneously, allowing easy passenger transfer in all directions.

Tramway See Streetcar

Transit signal priority (TSP) The control of traffic signal timing, and possibly street layout, designed to favor transit vehicles over private vehicles.

Truck See Bogie

Unlinked trip A trip counted separately, even if it may actually be a transfer between two transit vehicles.

Zonal service Transit service in which trains operate express or local along different sections of the route, with connections between zones only at a few joint stations.

Definition of the Subject

The term “urban public transit” encompasses a family of modes each serving a particular transport market. These modes can be arrayed by their costs and the quality of service they provide. Toward one end of the spectrum is the typical urban bus mode. At the other end are the regional rail systems with their high speeds and high capacities. In between, urban transit modes have ranges of cost and performance that overlap, and choosing between them may be difficult. Over the last several decades, the modes most often seen as competing for selection are bus rapid transit (BRT) and light rail transit (LRT).

This debate between the BRT and LRT advocates has too often been destructive, pitting two important urban transit modes against each other when the real “enemy” is the overuse and overfunding of the private car. Policymakers are often left more confused as they listen to the different opinions of their transit advisors. Sometimes they are led to believe that they will be able to save money with BRT yet get the same level of transit service and capacity as with LRT; in other cases they realize that an LRT solution is the better one even if it requires higher investment because of its stronger passenger attraction, permanence, and stronger positive impacts on the city.

What would be useful is to understand why and how the BRT and LRT modes evolved and what roles they play within a public transit network. Important in this context is to see BRT as several distinct services, each important, but few providing the speed and capacity of light rail transit.

Introduction

There has long been an ongoing debate in urban transportation on the role of bus and rail modes in urban transportation. That debate is actually a “subproblem” of the overall urban transportation problem – the relationship between public transit, private cars, pedestrians, and other modes. This problem occurs in all countries when auto ownership increases rapidly. The debate eventually defines the main issue: medium and large cities face the “collision of cities and cars.” The excessive traffic congestion caused by cars, which is wasteful, environmentally damaging and degrading to a city’s livability, can be solved either by extensive construction of highways and parking facilities or by controlling the use of private cars and offering competitive transit systems.

The policies of “adjusting cities to cars” were particularly strong in the United States. From 1945 to 1970, there was massive financial support for highway construction with negligible support for transit and the total neglect of pedestrians.

This wave of “auto mobilization” of cities also encompassed transit planning. A campaign swept the country against rail modes and for the replacement of streetcars by “flexible buses” in mixed traffic. This campaign, fueled by highway, car manufacturers, and the

oil industry, also actively worked against rail rapid transit systems. A major consulting firm developed an all-bus plan for Washington, D.C., a city that obviously needed rapid transit. The plan showed buses in huge underground stations with insufficient capacity, lack of signalization, and unacceptable exhaust gases. Moreover, the system would have required higher investment and operating costs than the rail. There was even a campaign alleging that “flexible” paratransit was more efficient for car-based cities than “fixed” rail transit.

Yet, even as the construction of metro and light rail transit lines intensified in dozens of cities in North America and around the world over the last 4 decades, extreme anti-rail transit views continue in some countries. In the United States, through the 1950–1970 period, the only urban transit modes to choose from were low-investment buses and trams (streetcars), and very high-investment rail rapid transit (metros or subways). The evolution of the tram into light rail transit (LRT), first introduced in Europe in the 1960s and then in the United States by 1980, gave urban planners a rail mode with some of the attributes of rapid transit that was more cost-effective in medium-density corridors and medium-size cities. This evolution was made possible by relocating trams from city streets and mixed traffic onto their own, separated (generally) at-grade rights-of-way.

Over the last 2 decades, a similar evolution has occurred with buses. Early on freeway bus lanes were introduced. Later, select bus routes on urban streets were upgraded through a series of smaller steps including longer bus stop spacing and preferential lane and signal treatments. As the ultimate step in this evolution, several cities have built largely grade-separated busways (e.g., Ottawa and Bogotá). This wide range of bus improvements was given the single label bus rapid transit (BRT) (Fig. 1).

However, the introduction of the BRT concept has again ignited a campaign that BRT can provide the same service as rail transit but at a much lower cost. As further discussion will show, BRT offers a different set of features than rail transit and it differs considerably from LRT, so that services of the two modes are by no means fully comparable. Nor are their permanence and impact on cities comparable.



B

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 1
Two BRT vehicles in Bogota, Colombia can carry all the people in the cars shown in six highway lanes

The debate between BRT and LRT advocates is important because policymakers who want to improve their transit systems often do not understand what each mode is able to deliver. The ongoing arguments among their advisors on the merits of BRT versus LRT are destructive for two reasons: they waste time and too often further delay already long-delayed decisions, and they play into the hands of those who are against any improvements to public transit.

This section reviews the evolution of both LRT and BRT and explains how each might meet the transit needs of cities. It defines the subcategories of bus services that fall under the umbrella term “BRT” in an effort to separate bus systems which have many LRT features (primarily separated ROW B, signal priority, and long lengths between stops) from buses which have only a few operational improvements.

Process and Controversies in Selecting Transit Modes

Civic leaders, transportation planners, and the public in general are increasingly recognizing that urban

transportation policies, specifically the selection of transit modes, have a major impact on the type and quality of transportation, as well as on the entire city’s character and quality of life.

Selection of transit modes is therefore a major step in urban transportation planning. Many factors that should be considered in comparing and selecting transit modes can be grouped into several categories:

- *System performance*: transporting capacity, speed, reliability, safety, comfort, and other elements.
- *Economic aspects*: investment and operating costs estimated for the projected quality of service, volume of attracted passengers, and applied fares.
- *Direct and indirect impacts*: The effects of the planned transit system on the area it serves and the entire city.
- *Role of transit on the livability, sustainability, and global impacts on weather change, energy consumption, and other broad aspects*: The planned transit line or network must analyze these long-term aspects, which are gaining increasing importance.

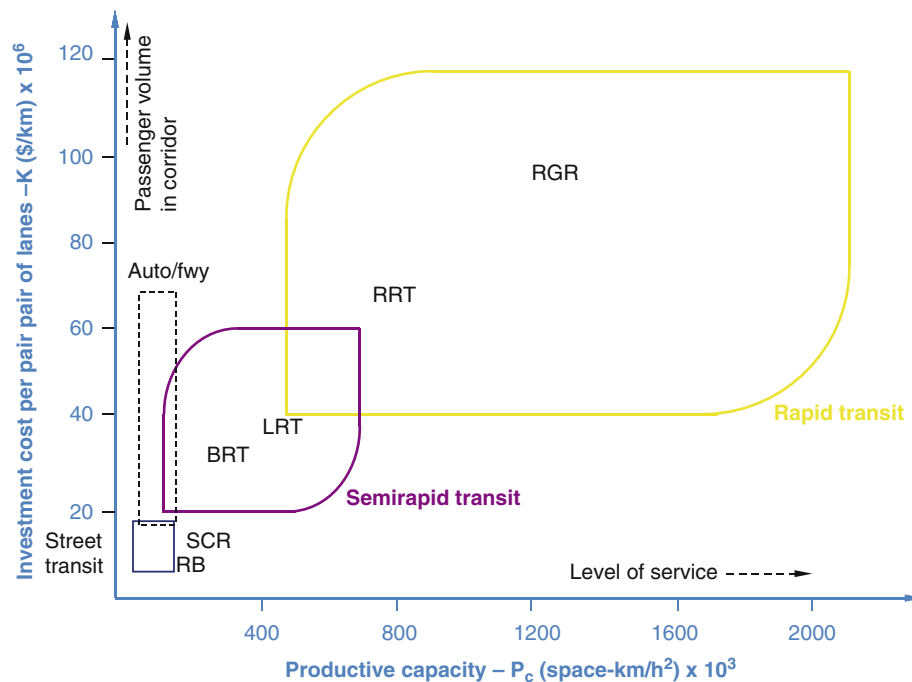
- *Quality and permanence*: Numerous other factors, such as the ability to protect the transit right-of-way from use by other vehicles.
- *Local preference*: The preference of the population for different transit modes.
- *Influences by different lobbies*: Groups (e.g., labor unions, business interests), often driven by financial interests rather than public interest, often wish to influence major transit decisions.
- *Type of service*: This characteristic includes line length and functional role (short-haul, regular city service or regional).

To compare transit modes systematically, it is very helpful to consider the elements that define modes. They are:

- *ROW category*: There are three types of ROW: A (fully grade separated), B (separated from other traffic), and C (within mixed traffic).
- *Technology*: Its main components are support (road or rail), guidance (steered or guided), propulsion (diesel or electric), and method of driving and control (manual or signalized).

While planning and attention to mode selection must be performed carefully, excessive controversies can be very harmful because they often cause long delays and lead to incorrect decisions, such as selection of a mode without sufficient capacity, with an inferior ability to attract passengers, or a mode that is later degraded by a failure to protect its ROW.

The “family of transit modes” can be formed by listing the modes from the lowest capacity minibuses on ROW C through medium-capacity modes on ROW B, including BRT and LRT, and AGT, metros and regional rail systems with long trains on ROW A providing the highest capacity and performance. When the average investment of these modes per kilometer of line is plotted on the ordinate, the diagram of the family of modes in Fig. 2 shows three areas with their increasing performance and investment costs.



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 2 Relationship between system performance (productive capacities) and investment cost of different generic classes of transit modes

Negative Trends in the Application of Urban Transit Modes Between 1945 and 1975

This entry discusses many of the factors that led to the creation of the distinct BRT and LRT modes.

Impact of Auto-highway Expansion on Selection of Transit Modes

Public transport companies, facing heavily subsidized highway construction for private vehicles and virtually no public assistance for transit investments and operations, were forced to convert their systems from electric streetcars and trolleybuses to motorbuses. Part of this conversion was logical when diesel buses were upgraded so that they became more economical and required less investment than streetcars on lightly traveled lines. However, conversion of heavily traveled streetcar lines, particularly those which had separated rights-of-way (category B), was made with explanations that streetcars were obsolete, buses were “more flexible” to mix with general traffic, their lines could be easily changed, etc. Such conversions were mistakes that led to downgrading of transit services in general.

If urban transportation is analyzed as a multimodal system, the nearly complete conversion of streetcars/tramways that was done in the United States, United Kingdom, France, and a number of other countries, had the following results:

- + Lower investment cost for line infrastructure (tracks and overhead cables)
- Loss of transit ROW B and the operation of “flexible” transit vehicles in general traffic, which resulted in reduced speed, reliability, and loss of distinct image of transit services
- Change from rail to bus vehicles which are smaller, less comfortable, have fewer doors, and cannot be coupled in trains (lower line capacity)
- Change from electric to diesel traction, which downgrades performance, generates exhaust gases and noise, and prevents operation in tunnels

Downgrading of Transit Services

There were secondary impacts of the conversion from rail to bus transit. In many cities conversion to buses was followed by the belief that “flexibility” of buses

should be used to replace a single heavily traveled line with high frequency of service by a large number of bus routes that provide better area coverage but have longer headways, lower speed, and reliability of service. Such extensive networks, which still exist in many cities, require less transferring, but offer services that have long headways and irregular alignments, resulting in low recognition and image. The belief was that copying services private cars offer would increase transit ridership. However, the opposite happened. Extensive networks of bus services with long and irregular headways attracted significantly fewer passengers than a smaller number of streetcar lines with frequent services.

Replacement of Streetcars by Buses Led to Major Losses of Passengers

The substitution of networks of rail lines having frequent, fast, and reliable services with extensive networks of infrequent bus services was not only less attractive, but in the long run its lower image and permanence diminished the role of transit and made it supplementary to private cars, particularly in small- and medium-sized cities. This was demonstrated by the fact that the number of passengers carried by buses in US cities consistently decreased even during the period between 1950 and 1970, when buses were introduced in many cities to replace streetcars.

Decreasing transit ridership, increasing traffic congestion and deterioration of cities led many cities to search for higher quality of transit services. The experience with “flexible” buses led to realization that making transit vehicles independent of general traffic is the basic element in achieving transit competitive with private cars.

Many cities tried to introduce reserved bus lanes, but found little support from traffic engineers, and great difficulties getting the police to enforce lane separation. The concept of LRT with tracks physically separated from other traffic by curbs was a logical solution to this problem, and since the late 1970s, about 20 cities in North America have introduced LRT systems with separated and protected ROW on their main lines. With the introduction of rail vehicles with greater comfort, more space, and higher speed than buses, many cities were very successful in reversing downward trend of transit ridership.

Two Major Trends in Transit Role Definition and Mode Selection: “Flexible Buses” or Upgrading Streetcars into LRT

Between the 1950s and the 1970s, policies on the selection of transit modes varied among cities depending on local conditions, methods of decision-making, financing sources, and the expertise of transportation planners and transit agencies. Nevertheless, a review of trends during this period of rapid car ownership increase in North America and Europe showed two distinctly different major groups of cities.

Cities with Policies That Encouraged Automobile Use: These policies facilitated unlimited private car use. They were followed in most US, UK, French, and Spanish cities, and they resulted in massive replacements of streetcars/tramways by buses in mixed traffic as well as extensive construction of freeways in urbanized areas. Metro was considered the only alternative for high-performance transit competitive with private cars.

Cities with Policies That Fostered Balanced Inter-modal Transportation: These policies implemented *parallel improvements* of streets/highways and transit

systems to achieve a balanced urban transportation system. They were the basic transportation policies in most cities in Germany, Switzerland, Austria, Benelux, and most Scandinavian countries as the only solution leading to livable cities. The main element in achieving transit competitive with private cars was recognized to be physical separation of transit, that is, the provision of ROW B and A. Selection of these separated ROWs made LRT the logical choice, because rail offers significantly higher performance, comfort, and image in the city, as well as greater permanence of transit ROW. These advantages were given more weight as, since the 1970s, most busways in the United States were downgraded into HOV facilities, greatly diminishing the priority of buses over other types of vehicles (Fig. 3).

The results of the two sets of urban transportation policies were drastically different with respect to mode selection as well as livability of cities. The cities which followed balanced transportation policies systematically upgraded tramways and buses on streets into semi-rapid transit modes to counter the increasing



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 3 Initially an exclusive bus roadway, the El Monte Busway in Los Angeles, USA has been degraded into an HOV facility, even allowing single driver hybrid cars

attraction of private cars, and to make transit independent of traffic congestion. The cities attempting to accommodate the increasing volumes of auto traffic found themselves with low-quality transit buses in ROW C facilities and with an inability to build extensive metro networks due to its high investment cost. Eventually, many of these cities realized that they needed transit modes that offer much higher performance than do buses on streets, but at significantly lower investment costs than metro systems. The LRT mode met this requirement, and it has been built in dozens of cities in the United States, France, United Kingdom, Spain, Canada, and others. Later development of the BRT mode provided another opportunity for these cities to build medium-capacity modes, narrowing the “gap” between buses on streets and metro systems.

Inherent Differences Between Industrialized and Developing Countries

What follows is a generalization. There are, of course, wide differences between particular nations, and even cities within the same nation. Moreover, some economies have such rapid development that the context for planning transport is continually changing. While rapid change increases the need for dramatic action, it also increases the risk of unforeseen consequences from implementing a project. The following are conditions that make the selection of modes in developing countries different than their selection in industrialized countries.

Demographics: Richer countries, by definition, have a population with more travel mode and destination choices. Thus, most new public transportation enhancements in such countries must pay heed to the needs and desires of so-called “choice” riders. While the fare levels are not unimportant, they are less important than creating attractiveness for persons who can afford the high investment and operating costs of auto ownership.

By contrast, in developing countries a large percentage of the population is “captive” riders. They will be either walking or using public transportation. They are much more sensitive to the fare level. If the fare level can be kept very low by allowing greater crowding, this option is often employed even at the expense of losing many choice riders.

In rapidly developing countries there is a need for public transport investments that address both choice and captive riders. On the one hand, suppressing auto use by affluent persons becomes an important goal. On the other hand, an increasing population of lower and medium-income persons and higher development densities demands a goal of providing high capacities with moderate fares. The question then arises whether one mode can address both goals simultaneously or whether different systems must be built for different passenger segments.

Wage levels: Public transport systems in the developed world typically use 70–80% of their operating budget for salaries, wages, and fringe benefits. Thus, it becomes of vital importance to identify and employ technologies that increase worker productivity. Some well-capitalized public transport systems have seen continuing increases in service output with little increase in staff size. The ability to increase consist size without additional drivers is one of the main reasons for upgrading high-demand bus corridors to rail modes. Furthermore, state-of-the-art self-service fare collection like pay-by-phone, computer-aided dispatching for field supervision, Internet-based itinerary planning services, and other advanced technologies can pay for themselves. The ultimate productivity gain is conversion of rail lines to full automation to remove the driver.

By comparison, well-organized transit agencies in developing countries often pay a small fraction of the hourly labor rate paid in richer countries, and with fewer benefits. At the same time, funds to purchase advanced technologies are likely to be scarce. In such an environment, the case to go to rail technologies, or even to larger buses, is not as compelling.

Employment policies and labor regulation: In many developing countries, governments view public transport as a significant source of employment. In some cases, publicly owned services are overstaffed. In many more cases, the vast majority of transport services are provided by owner-operators or persons renting or leasing vehicles from owners of bus fleets. In such situations, attempts to build public transport networks on high-capacity corridors using very large vehicles often meet strong opposition. A recent and dramatic case is the entirety of South Africa. Efforts to design BRT networks in Gauteng (Johannesburg-Pretoria),

Cape Town, and Nelson Mandela Bay all met intense, and even violent, opposition from minibus syndicates.

While it may be logical to suggest that the mobility of millions of persons is more important than the employment of a few thousand persons, it is a fact that politicians can be very wary of labor opposition, particularly in the context of high unemployment. In such cases, the higher labor productivity of rail or large BRT buses is not a particularly strong selling point. (Actually, rail systems do have a lot of other employment in track, station, and vehicle maintenance.)

Financing capacity: The ability to finance major construction projects can be a problem for many cities even in the richer countries. For many poorer cities and countries, it means increasing taxes or depending upon international investment banks that attach conditions to their grants and loans. Either option can be unattractive to politicians.

One of the consequences of the difficulty to finance transit projects is the controversy between building BRT and metros. This is true even for very large cities that need the capacity of a metro due to large populations, long travel distances, and severe street congestion. The choice in such cases is often between the lower investment costs per kilometer of lower-performance BRT, or the higher investment for a higher performance and more permanent rail system.

Organizational capacity and effectiveness: In many developing countries, the existing institutions at the city, regional, and/or national level do not have the ability to design, build, or manage modern high-capacity public transport systems. This lack of capability acts as a deterrent to even consider many projects. One case is instructive. A need for a metro network in Delhi was recognized in 1997, but neither the national government nor prospective international lenders believed that the existing public agency could design, build, or manage such a system given its record of gross overstaffing and inefficiency. Thus a new corporation to be headed by a proven manager was created. In the end, the corporation not only built an excellent metro rail system, but it was well poised to compete against international firms for future projects in other Indian cities.

Public participation: Most of the industrialized countries have public participation laws designed to allow affected parties as well as the average citizens to influence the design process. These laws are a democratic response to cases where citizens receive a new transportation project that they would not have selected had there been more input. This process slows down the design effort, but it also presumably results in a more beneficial and just project in the long run.

Many developing countries, even with well-intentional planners, do not have formal public participation processes. Thus, planners must design systems with less knowledge of the needs and desires of potential users. The technical expertise of planners and engineers is therefore of primary importance.

On the other hand, in some developing countries governments have greater powers than in democratic industrialized countries. This can make the design and build steps far easier, quicker, and more efficient.

Right-of-way acquisition: Obtaining reserved ROW B is the basic element determining the feasibility of semi-rapid transit, BRT or LRT. The possibility of getting a protected ROW depends on many factors, often different in developing and industrialized countries. Advocates of BRT claim that 8–10 m strips of land can be obtained easily in many developing countries because auto traffic volumes are lower than in industrialized countries. However, in numerous cases the expected acquisition of such rights-of-way has proven to be unrealistic.

The reasons for this discrepancy of theoretical claims and real-world implementation are many. Although car ownership in those countries is still low, street traffic congestion is often even more acute than in industrialized countries because their streets are even more congested by trucks, minibuses, rickshaws, taxis, bicycles, pedestrians, and other participants. The diversity of modes makes traffic conditions even more chaotic and difficult to regulate. This makes acquisition of protected traffic lanes extremely difficult. For example, in several cities, fleets of buses that were bought for planned BRT systems had to be stored in expectation that the BRT infrastructure will be built later. In Jakarta, there were legal challenges of exclusion of

other traffic from bus lanes, while in New Delhi regulations allowing and prohibiting taxis from BRT lanes was changed several times.

In industrialized countries there is also a major difference between BRT systems in theory and in practice, but for different reasons. A number of successful reserved busways with most BRT elements were downgraded by their conversion to high occupancy vehicle (HOV) lanes. The decisions for these changes were made by judges in courts (discontinuance of HOV lanes on the Santa Monica Freeway in Los Angeles), by city councils (discontinuance of a bus mall in Philadelphia), by state legislatures (conversion of the El Monte Busway in Los Angeles to HOV lanes), and by other bodies which have no professional expertise in urban transportation.

Decisions to retain the exclusive use of busways by buses or to allow other vehicles vary among cities and countries. In the United States, many exclusive busways have been downgraded to HOV facilities, in many cities taxis are allowed to share busways, and most recently hybrid passenger cars are given this privilege. In Madrid, motorcycles are permitted in busways.

Modal integration: In the more developed countries, it is common for one agency to either provide all services, regardless of mode, or else manage them under one coordinated fare structure. The operator of a particular vehicle in no way depends upon the fares collected (or not) from boarding passengers. In such an environment, it is possible to institute significant or even total network reorganization with the advent of a new mode. Thus the lower income person is not unduly penalized for needing to transfer between services.

By contrast, most developing countries have cash-based operators that depend on retaining all or part of the money collected. At the same time, riders are forced to pay a full fare each time they switch between vehicles or modes. Thus, both the operators and riders have reason to oppose the imposition of a new higher-capacity mode within their existing network. The former sees a revenue loss and the latter sees paying additional fares to use the new service.

Traffic enforcement: Police control and enforcement of exclusive transit rights-of-way is very different for

the two semi-rapid transit systems. LRT requires very little police control, mostly limited to intersections. A BRT lane, when it is immediately adjacent to other traffic lanes, is always attractive to road vehicles traveling in other lanes, so that police enforcement must always exist at intersections and bus lanes between intersections.

Police enforcement depends on local police effectiveness, which varies among cities. For example, cities like Singapore and New York have stricter controls than Boston and Moscow. Similar variations exist among cities in developing countries, but in many of their cities the practice of bribing policemen degrades the traffic discipline even more.

Light Rail Transit

Cities which adopted policies of implementing balanced transportation concentrated on upgrading transit by developing rail transit networks on ROW categories B and A. This has been the most important measure making transit independent of street traffic congestion and therefore competitive with the private automobile. Transit on exclusive ROW logically led to the development of advanced articulated rail vehicles, increased operating speeds, reliability, comfort, and safety.

Major changes in medium-capacity rail transit, most of which took place in Germany, The Netherlands, Belgium, and several other European countries, created a transit mode that is actually more similar in its performance and efficiency to metro/rapid transit than to conventional streetcars/tramways, so that it was given a new name: light rail transit, LRT, or Stadtbahn in German (Figs. 4–6).

Development of LRT Mode

Following several decades of system design, rights-of-way development, and technical and operational innovations, LRT has become a very diversified mode. The most significant innovations that led to the creation of LRT and its introduction in dozens of cities are listed in the box below.

It is interesting to note that during the 1970s and 1980s many cities built tunnels for center-city sections of LRT to make their operations as close to the metro as



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 4
Tramway on ROW category C in Milan, Italy



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 5
LRT on ROW category B in Paris, France

possible. This was the case, for example, in Frankfurt, Stuttgart, Edmonton, and Hannover. Since 1990, however, an increasing number of cities have designed LRT systems that run through pedestrian zones with

decreased or eliminated general traffic. For example, in cities like Strasbourg, Calgary, Denver, Barcelona, and Istanbul, LRT trains travel through central cities at lower speeds than tunnels would allow, but that often



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 6
LRT on aerial structure in Los Angeles, USA



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 7
LRT within a pedestrian zone in Karlsruhe, Germany

does not result in longer passenger trips because it eliminates for passengers the time and effort of walking two levels into and out of underground stations (Fig. 7). Heavily traveled lines with longer trips and

a need for higher speed are, however, still being placed in tunnels, on aerial structures or other types of exclusive ROW, as is the case in Dallas (Fig. 8), Cologne, Copenhagen, St. Louis and Rouen.



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 8
High-capacity high-speed LRT train in Dallas, USA

Major Steps in the Development of LRT and Its Role as the Leading Medium-Capacity Transit Mode

- Consolidation of extensive tramway networks into fewer, high-performance LRT lines.
- Systematic replacement of ROW C (street running) by ROW B and A, that is, separated ROW.
- Use of street medians, tunnels, or aerial alignments on the same lines.
- Intermodal integration with bus and metro lines through construction of joint transfer stations.
- Development of high-quality rails and switches that provide quiet and virtually perfect riding comfort, far superior to buses and rubber-tired AGT systems.
- Articulated vehicles offering spacious comfort, operated as one- to four-car trains up to 90 m long with capacities as high as 750 spaces.
- Change from unidirectional tramway-type to bidirectional metro-type rolling stock.
- Self-service fare collection allowing rapid boarding/alighting of passengers on all doors and use of any type of fare.
- Low-floor (0.25–0.35 m above top of rails) vehicles facilitate boarding/alighting of all passengers and meet the needs of the disabled.
- Because of increased TU capacity, one-person crews, and increased operating speeds, the

productivity of operating personnel (expressed as passenger-km/h/driver) has increased about 20 times from tramways. Productivity is also about five times greater than on the highest capacity BRT (750 vs 150 spaces per driver, not considering typically higher operating speeds of LRT than BRT).

- Operation of LRT in central cities is performed effectively in tunnels, or, in many cities, by running directly in pedestrian malls and zones (with lower operating speeds on such sections).
- Integration (track sharing) of LRT with regional rail lines for services to suburbs and nearby cities.

Major Types of LRT Applications

Successful construction of LRT in many European cities led to numerous professional conferences and the adoption of LRT as the leading medium-capacity transit mode in many countries which had eliminated streetcars/tramways during the 1950–1970 era: United States, Canada, France, United Kingdom, Spain, and a number of others. During this new wave of building LRT since the 1970s, about 100 cities have either expanded or built new lines and networks. In many cities one or several new LRT lines have become the main transit system carriers with significant increases

in transit ridership. This was the case, for example, in San Diego, Calgary, Sacramento, Portland, Strasbourg, Bordeaux, Sevilla, Birmingham, Denver, and many others.

The successful introduction of LRT in so many cities of different sizes and characters is largely due to the extreme diversity of characteristics of the LRT mode. An analysis of the present broad family of tramway/LRT modes has defined ten categories of this mode by its physical, operational features and role it plays in the city's transportation. They are listed in the box below.

Ten Categories of LRT and Its "Neighbors": Tramways and Mini-metro Modes

1. Conventional tramway mostly with ROW B and C: Melbourne, Moscow, St. Petersburg, Toronto
2. Modernized tramways with signal priority, improved stops, prepaid fares, etc.: Amsterdam, Oslo, Prague, Vienna, Zurich
3. New tramways built in redesigned pedestrian-oriented city centers (some also using historic vehicles as center-city shuttles): Grenoble, New Orleans, Nice, Portland Streetcar
4. LRT developed from upgraded tramways: Berlin, Cologne, Rotterdam, San Francisco, Stuttgart
5. LRT with metro network: Boston, Brussels, Philadelphia
6. LRT systems in suburbs of megacities: Hong Kong (Tuen Mun), London (Croydon), New York (Hudson-Bergen), Paris (lines T1, T2, and T3)
7. New high-performance LRT systems: Birmingham, Calgary, Dallas, Denver, Nantes, Portland, San Diego
8. Light Rail Rapid Transit (LRRT): LRT on ROW A only, also referred to as a "mini-metro": Kuala Lumpur, Manila, Philadelphia (Norristown Line)
9. Automated LRT: same as #8, but fully automated and without driver: Copenhagen, Kuala Lumpur, London (Docklands), New York (JFK Airport), Vancouver (Skytrain)
10. LRT/Regional Rail integrated systems, popularly (although incorrectly) known as "Tram-Train": Bern, Karlsruhe, Kassel, Manchester, Saarbrücken

Review of LRT Characteristics

An analysis of the development and broad deployment of LRT in many cities shows that this transit mode has many characteristics that make it an optimal solution for cities that need medium-capacity transit systems, that is, those that perform much better than regular buses on streets, but require a substantially lower investment cost than metro systems. Main characteristics of LRT are summarized in the following box.

LRT has several other physical characteristics that distinguish it from road vehicles. First, being a guided system, LRT uses considerably wider and longer vehicles than buses and it can operate in trains. With the high capacity of transit units, LRT can provide a higher line capacity per track than road vehicles can provide per lane. Second, electric propulsion gives LRT systems better performance (acceleration, grade-climbing ability, braking with regeneration of energy), no exhaust or noise along the line, and the ability to operate in tunnels, which vehicles with internal combustion engines do not have. Finally, rail technology makes signalization, automatic train protection (ATO), and other automated safety features possible, so that LRT can operate at higher speeds and at a higher degree of safety than road vehicles.

Positive and Negative Characteristics of Light Rail Transit Compared to Its Peer Medium-Capacity Modes

- + Rail guidance technology has a simple basic mechanism: four to eight wheels per vehicle running on two steel rails.
- + The simplest, fastest, fail-safe switching of all guidance technologies.
- + Steel-wheel-on-steel-rail contact produces extremely low rolling resistance, so that rail modes require the lowest energy consumption per ton of weight of all presently operational transit modes for any given dynamic performance.
- + Rail is the only guidance technology that allows not only at-grade crossings, but also on-street running.

- + Its simplicity and ruggedness give rail technology low maintenance requirements and high durability.
- + It copes better with adverse weather conditions (rain, snow, and ice) than rubber-tired technologies.
- + Modern rail vehicles provide virtually the ultimate in stable, smooth riding comfort.
- Investment cost of rail lines is higher than that for buses, but lower than the cost of other guidance technologies, such as Rubber-Tired Rapid Transit and Maglev.
- The lower adhesion coefficient of steel-on-steel than rubber on dry concrete surfaces gives LRT and other rail modes two relative disadvantages.
- Rail systems cannot negotiate as steep gradients as can rubber-tired systems.
- They must be operated with higher degree of safety because of their longer stopping distance.
- Although modern rail vehicles run extremely quietly on straight sections and mild curves, when negotiating sharp curves, rail vehicles produce more noise and vibration than do rubber-tired vehicles.

Roles and Impacts of Light Rail Transit

The interaction of transit systems with land use planning, physical form, and quality of life in cities is mainly dependent on the infrastructure of the transit system. While transit modes with flexible routings, such as buses on streets, do not have much impact on city planning and form, permanent infrastructure of guided systems provides the certainty that investment decisions require, so that LRT can be used to influence the form and character of a city.

Mayors of several cities which have recently built LRT systems, including Portland, Denver, and Salt Lake City, have often pointed out in their speeches that the introduction of LRT did not only improve transportation services, but it changed the character and increased the livability of their cities as well. Similarly, many cities in France, Spain, Ireland, and other countries have used the construction of new LRT systems as the pivotal project for the reconstruction of entire corridors or central urban areas to make them more pedestrian-oriented rather than car-dominated. Good examples of this are Strasbourg, Lyon, Toulouse, Nice, Dublin, and Valencia (Spain).

Upgrading Bus Services into Bus Transit Systems and Bus Rapid Transit

Local bus routes are the workhorses of the transit industry, and must operate under challenging conditions. They operate in mixed traffic like all other vehicles. They have no signal priority, and only rarely any reserved bus lanes. They serve many bus stops, often 150–200 m apart, which vary from a small sign on the side of the road to shelters and benches. The driver does fare payment and control at the front door. And local bus routes necessarily serve both short, local trips and long, commuter trips.

Over time, a number of measures that incrementally improve local bus services have been developed and gained increasing acceptance. Taken together, they provide a level of service that has become popularly known as bus rapid transit. Unfortunately, BRT is a term that has been too loosely used to describe too wide a range of bus service enhancements. This has somewhat tarnished the term.

This chapter will first review efforts to make buses act more like light rail within their own guided rights-of-way and within their own tunnels. Concurrently, bus planners began to focus on taking the bus mode and greatly improving its physical and operating environment. The next section will discuss those measures that have given buses preferential treatment in its ongoing struggle with all other vehicles using the streets.

Guided Buses and Buses in Tunnels

In the late 1970s and early 1980s, there were a number of guided busways proposed and a few were built. These efforts were attempts to provide the bus mode some of the attributes of rail transit, or at least make them appear to have the attributes of rail transit: speed, safety, and exclusive, narrow rights-of-way. Other applications used various mechanical arms or wheel assemblies to allow buses to track a raised, guiding curb. Anything raised, of course, made it difficult to move across intersections, and interrupting the contact with the raised curb proved too unsafe. Other designs used electronic or optic sensors to guide the vehicle.

The most lasting of these guided buses was the German O-Bahn concept that was initially built in Essen, Germany, but that test track did not get extended and has been superseded by light rail.



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 9
Sole major O-Bahn system in Adelaide, Australia

An O-Bahn was also built in Adelaide, Australia, and it is still operating there. This concept uses concrete beams with guiding curbs within its own, fully grade-separated right-of-way. This design proved successful to install, if expensive. It has not been replicated elsewhere, except for a few short sections of bus lines (Fig. 9).

Several bus tunnel projects were built to allow buses to avoid surface congestion. The first such project in America was Pittsburgh's original South Busway opened in 1977. It made use of an old tramway tunnel that was converted to serve both buses and light rail trains. There are, however, no stops or stations in the tunnel. The 2.1-km Seattle Bus Tunnel began construction in 1987 and cost \$450 M to complete. Operations began in 1990 using dual-mode diesel-electric trolleybuses. It became a joint bus and light rail tunnel in 2007. The older buses, which cannot operate with the light rail overhead catenary system, have been replaced with new diesel-electric battery hybrid buses. Thus, tunnels for BRT have cost in some cases more than tunnels for rail modes, including LRT and metro systems.

By far the longest bus tunnel built in North America has been a section of the Silverline near South Station in Boston. The project was poorly conceived and represents an extremely expensive facility with very poor results. This bus tunnel cost about \$500 million per mile (\$350 million per km) to build. To solve the

problem of diesel motor exhaust, dual-mode (diesel/electric) buses have been introduced. The tunnel has curves with limited sight distances, but has no signal protection, so that speed is limited on different sections to 10–20 km/h. At the exit of the tunnel, there is a traffic signal that further delays trolleybuses 1–2 min. The line then continues to the airport, where buses stop along a frequently congested four-lane roadway. Picking up passengers with luggage who have to pay fares on board also slows the service down.

The Silverline in Boston demonstrates that claims that BRT is always much cheaper to build than LRT is not correct. Actually, in many cases (Seattle, Boston) BRT tunnels have involved much higher investment cost and provided much lower system performance than rail tunnels.

The Development of Bus Preferential Treatments

For many decades buses were treated no differently than any other street vehicle. The result was slow service and poor reliability. Gradually, planners began to realize that providing preferential treatment for buses increased transit speeds, attracted riders, and lowered operating costs. These have increasingly been incorporated into street designs, but there is still a reluctance to provide buses with the priority that their higher passenger loads warrant.

Intersections are where a number of improvements can be made. One basic improvement is to allow buses to go through an intersection from a right-hand turn lane where there is often a bus stop. Providing a lead “queue jumping” green signal from this lane or a “bypass” lane through the intersection also reduces travel time.

The separation of buses onto their own lanes provides much more benefit, but this is often quite difficult in a congested city and is done, even now, only rarely. Reserving the curb lanes for buses is the most common approach because bus stops can still be on sidewalks. Bus lanes can also be located in the center of streets. This is usually an expensive proposition, however, because streets may need to be further widened for bus stops, turn lane storage, etc. Contraflow bus lanes take advantage of wide streets or street pairs to carve out the necessary travel way for buses; in the proper place they can be useful.

Finally, buses have begun to be given (by traffic engineers) various levels of traffic signal priority (TSP). TSP for bus transit usually comes in the form of a “green wave”, or “green extension/red truncation” which is limited, for example, to less than 10% of the cycle length. While traffic engineers may give signal priority to buses at many intersections along the route, they are rarely given at all intersections.

A higher level of transit signal priority is traffic signal *preemption*. Light rail trains are almost always given traffic signal preemption when operating faster than 35 mph and preemption often comes with crossing gate protection. These gates are justified because the weight, speed, and long stopping distances of trains require stronger protection and allow higher transit speeds than buses.

Express Bus Services

The first step often taken by transit agencies to enhance local bus services is to supplement the route with limited-stop service. Fewer bus stops means shorter travel times for passengers going longer distances. This is especially appealing during peak commuting hours, which is when many limited-stop bus services operate. Reducing bus stops is a prerequisite for all higher levels of bus operations.

Other than fewer stops, however, many of the features of local bus services remain: no preferential

treatment, no dedicated bus lanes, onboard fare payment and control, and no special amenities or service branding.

Enhanced Bus Transit Service

These services add further travel time savings to limited-stop bus services. They retain and even reduce the number of bus stops of limited-stop bus services. They included bus stops with improved shelters and seating, arrival-time message boards, and if possible extended-curb bus stops that remove the time buses lose moving out of, and then back into, the flow of traffic. Special bypass lanes at intersections, lead “queue jumping” green signals, and special turning lanes can help give buses an advantage at busy intersections. Priority signal treatment that gives approaching buses an extended green signal can be a significant travel time improvement. The ultimate improvement is to give the buses their own bus lanes separated from other traffic. However, as noted above, rarely are designated street lanes of any length given over to bus operations.

Bus services with enough of these enhancements are often branded to reflect their special status and service quality. Often newer, articulated, cleaner-energy buses with special paint schemes and catchy names are used to differentiate these services. For example, this network is called Metro Rapid Bus in Los Angeles, Special Bus Services (SBS) in New York, and the Silverline in Boston.

Although these types of services are often given the label BRT, they usually do not include enough enhancements to warrant the label. Enhanced bus services typically lack three key timesaving features: fully separated bus roadways, off-bus fare collection, and traffic signal preemption.

At-Grade Busways

There are at least two major at-grade busways in the United States: the South Miami-Dade Busway and the Los Angeles Orange Line. The Eugene, Oregon’s Emerald Express busway may be another, although it does not have the same level of treatment the others do. (Seattle has an approximately 2 km long busway segment south of the bus tunnel.) The first two facilities appear to have all of the ingredients needed to provide service comparable to light rail. They operate over



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 10
The Orange Line BRT in Los Angeles on ROW category B uses articulated buses to increase line capacity

separate bus roadways; they have off-vehicle fare collection; they have traffic signal priority at most intersections they cross; and they have only limited service over city streets. To make up for the inability to train-line buses, these busways use longer, articulated buses to provide more line capacity (Fig. 10).

That being said, the service provided is not comparable to light rail operations. The main reason is that neither the Orange Line nor the South Miami Busway has crossing gates and therefore both must slow to below 32 km/h (20 mph) at each intersection, even with signal priority [1]. The use of crossing gates with at-grade busways has not been allowed by traffic engineers because their operation takes too much green time away from cross traffic [2]. At some intersections the buses on the Orange and South Miami-Dade Busways have no signal priority at all.

Crossing gates are mandatory for LRT above a certain speed typically 55 km/h (35 mph). Because of them, ROW B for LRT can act like a ROW A by providing full protection for the light rail train.

Bus Transit System: BTS

As mentioned above, regular bus services in many cities, including most US cities, are operated very inefficiently: they have stop spacings of 150–300 m (at every intersection), passengers board and alight at any

door, colliding with those who are boarding and trying to pay through a single channel door; many buses do not stop close to the curb; there are few bus lanes and nearly no signal priorities at any intersections. Recent efforts to improve such operations have been rather liberally given the term “bus rapid transit.” This trend has resulted in downgrading the BRT concept and caused confusion.

This text uses three definitions of bus systems. Regular, conventional (and often inefficient) bus services are referred to as “Regular Bus – RB.” Bus services which are improved in station spacings, operations, etc., similar to many bus services in European countries and those in US cities which have been upgraded, are designated here as “Bus Transit System – BTS.” Finally, “bus rapid transit – BRT” are the systems which have distinctly higher performance with elements defined rather precisely in the following section.

Bus Rapid Transit

Definition of Bus Rapid Transit There is a consensus [3] that bus rapid transit is a bus system that has the following elements superior to regular bus systems:

1. Reserved (physically separated) lanes or roadway – ROW B or A not shared with other vehicle categories (taxis, HOVs, and others)

2. Distinctive lines with frequent, reliable service and regular headways during all daily hours
3. Distinctive stops with passenger information and protection spaced at least 300–600 m
4. Distinctively designed bus vehicles with large door-to-capacity ratios, low floor, or high platforms
5. Bus preferential treatment at all signalized intersections
6. Use of ITS technology for monitoring vehicle movements, passenger information, and fare collection

However, this definition is rather “idealistic,” because there is virtually no bus system in the world that has all these elements. Therefore, it is considered that BRT is a system that has most of these elements.

Several bus systems in the world have achieved an exceptionally high quality and fall in this definition of BRT. Often cited are Bogotá’s TransMilenio (Fig. 11), Brisbane’s Busways, and Ottawa’s Busways. Pittsburgh’s Busways could be among them if its image and other elements (station amenities, off-board fare collection) were improved.

The most important requirement for a busway to be comparable to an LRT line is to give it a similar right-of-way and, therefore, a similar operating speed.

Because at-grade busway buses will not get the same signal preemption as do light rail trains, greater emphasis – and investment – must be made to give busways more grade-separation at intersections. The need to provide a high level of priority is particularly true in the central business district when a 90 km/h (55 mph) approach on a busway can degenerate into an 15 km/h (9 mph) slog through congested downtown streets. Successful BRT systems try to make this investment (Fig. 12).

BRT stops are also well spaced and more like stations with good weather protection, seating, a sense of security, and real-time bus arrival information. These elements are common with LRT stations, but are too often short-changed on busway lines.

BRT systems use large buses with wide doors for easy and rapid passenger exchange. Articulated buses are common and even double-articulated buses are used. To help market the better BRT service(s), its buses have special bus colors and logos.

BRT systems try to provide BRT buses any preferential treatment necessary through any at-grade intersections or bottlenecks off the ROW A. A number of such measures were discussed in the preceding section. It does little good to have great service only on that portion of the bus route that is fully



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 11
Bogotá TransMilenio BRT line



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 12
Bogotá's BRT distribution through central city pedestrian area

grade-separated if the overall experience of the passenger is mediocre.

BRT systems monitor all aspects of their operation to make sure buses are on time and safe, to provide the traveling public with real-time arrival information and respond to their questions, and to process quickly and efficiently the collection of fares.

BRT systems have robust bus operations with several types of services available. While there is typically the busway-only service equivalent to a light rail line, there may also be express bus services and services typical of a freeway busway with suburban bus routes using the common busway trunk segment. Two things make such a complex operation possible: the design of the busway that allows buses traveling in the same direction to pass each other and the full grade-separation of the busway. This mix of bus operations is beyond the abilities of almost all light rail systems. The extra tracks needed for trains to pass other trains traveling in the same direction are rarely built. Express trains may skip-stop or be scheduled to just catch up with a local train ahead, but do not pass the local train.

True BRT is not “cheap LRT” or “LRT Lite” [4]. Building a substantially grade-separated busway with well-designed stations can be very expensive, particularly within the congested central city. But with a robust

and well-conceived service plan using several types of bus routes the resulting service can have some advantages over LRT with respect to easier introduction of line connections, branches, and express/local services if stops have four lanes (see Fig. 11). It is, however, doubtful that a BRT line can achieve on any given ROW width (two tracks/lanes, or four tracks/lanes) the capacity of a light rail line capable of coupling multiple cars into a single unit.

BRT Evaluation: Successes and Failures At this time (2011), the broad experiences of recent decades achieved by dozens of cities – and demonstrated by cities recognized as leaders in efficient transportation that contributes to their livability and sustainability – can be summarized in the following major points:

- Balanced intermodal transportation is greatly superior to transportation systems based on car dependency, meaning excessive restrictions on certain major modes such as transit, walking, or bicycling, or impracticalities on their use.
- Balanced transportation must incorporate and favor public transit systems which consist, particularly in medium and large cities, of different integrated modes, such as buses, BRT, trolleybuses, LRT, metro, and regional rail.

- Large cities, with more than one million people, usually have rail modes as their main carriers, but rail systems cannot achieve their full potential if they are not complemented by and integrated with buses.

There have always been promoters of individual modes claiming that they are superior to other modes. The strongest such pressures have been for private cars, and their political successes have created car-dependable cities that are inferior to intermodal cities with respect to quality of life, economic vitality, and sustainability. Single-mode promoters have also caused “waves” of discussions that the most efficient modes are paratransit, monorails, various automated guided systems (AGT), including the totally infeasible personal rapid transit (PRT, now reappearing under the name “Pod cars”). These extremist views that a single mode is the dominant or only solution for all cities have eventually been discredited. Intermodal transit systems utilizing the diverse family of transit modes, from historic streetcars to BRT and regional rail systems, are obviously the trend for the future.

To be fair, promoters of single modes have fostered some useful innovations. Paratransit has become more diversified since the 1970s. Some 2 dozen monorails have been built in various cities, and AGT systems are used in an increasing number of airports as well as for transit lines in some cities, particularly as downtown circulators.

It is unfortunate that BRT, which has brought very significant progress to many cities, is promoted by some organizations, government bodies, and individuals as the single mode superior to all other modes. This fringe of extremist BRT promoters is actually causing considerable harm by weakening the concept of intermodal transit and by actually strengthening the already dominant pro-automobile lobbies. Finally, these “BRT evangelists” harm the cause of BRT by promising that this mode can solve all transport problems, so that its problems or failures in different cities lead to questioning the value of the entire BRT concept.

Many elements of BRT were introduced during the 1970s and 1980s in several cities, although the term “BRT” had not yet been coined. São Paulo developed several high-density corridors with high-frequency

service by buses and trolleybuses utilizing four-lane stations with overtaking of buses, platooning of buses from different branches for increased capacity on the joint trunk, etc. Pittsburgh, Washington (Shirley Highway), and Los Angeles (El Monte) introduced busways, although more for commuter services than for regular transit. Ottawa built a network of busways and made more integration of their services with land use planning around their stations. (The limitation of this system has been that its busways lead into downtown streets, which represent a capacity bottleneck for the entire network.)

To clarify the strengths and limitations of the BRT mode, several leading BRT projects are evaluated here.

Curitiba: Following innovations in bus system design in various cities, Curitiba in Brazil built a network of BRT lines which is still considered the best planned one because it was designed as an integrated part of the city’s land use plan. The BRT lines represent the spines of major corridors with high-density buildings throughout the city.

In addition to the planning aspects, Curitiba became the leader in designing high-level platforms and high-floor buses for level boarding/alighting through wide doors on articulated and double-articulated buses. Fare collection at the entrance to specially designed stations in the median of the busway was another element that increased line speed and capacity. Curitiba is considered as a leader in the development of the BRT concept.

Bogotá’s TransMilenio BRT System: This BRT system has drawn great publicity and is called by some the “Gold Standard of BRT.” It is therefore useful to examine its strengths and achievements, as well as its limitations and shortcomings.

The city of Bogotá, capital of Colombia, suffered from chronic congestion that was getting steadily worse with its growth of population and car ownership. It was served by remarkably primitive transit services consisting mostly of 8- and 10-m long private bus lines without any coordination, integration, or joint fares among hundreds of companies and individuals who owned and operated them. The city faced two problems: how to organize transit services into a coordinated system, and then how to build a network of high-capacity semi-rapid (mostly independent) or rapid (fully separated) transit lines.

Rail rapid transit was planned for a long time, but problems in coordinating, organizing, and financing the project stalled progress. Then, under the leadership of Mayor Enrique Penalosa, a BRT system was built for a major corridor, opening in December 2000. This was followed by other lines, which now represent a network of high-capacity lines.

The achievements of TransMilenio are quite remarkable. The system represents a huge leap forward over the chaotic, low-quality and low-capacity disintegrated bus lines. These small-bus services still carry the majority of trips in Bogotá and still represent a serious problem because of their poor service quality and inability to attract choice riders. The TransMilenio system has successfully attracted a substantial portion of trips and provided them with much faster and more reliable services. Now, finally, the city with a population of about seven million persons and growing has an increasing network of fast lines largely independent from street congestion, which also reduce the traffic loads and congestion on existing streets.

Along with these significant achievements, TransMilenio has several serious limitations, which should be carefully considered in further transit planning for the city. They are:

- The success in attracting very large passenger volumes is overwhelming the system. TransMilenio operates at and beyond its capacity for long periods of the day. That results in extremely low passenger comfort and lower service reliability than the system could provide with below-capacity passenger volumes.
- TransMilenio busways are located in the median of corridors with 8–12 traffic lanes that can be crossed by pedestrians only via long overpasses provided at distances of several hundred meters. This design provides only a single access to every bus station, so that walking distances from the closest buildings and streets to a bus station entrance amount in many cases to several hundred meters and involves crossing ramps and bridges unprotected from the weather. This design is very unattractive to users, reduces the competitiveness of transit services for car owners, and represents a major divide between streets and buildings on its opposite sides. This is the opposite impact on a city's livability from the

impacts that LRT services have when they go through pedestrian zones.

- While electrically powered rail transits (LRT or metro) provide quiet vehicles without exhaust and long-term sustainability, buses with diesel or other internal combustion engines represent a much less attractive alternative. Thus, in the choice between BRT and LRT or metro, buses represent a major step backward with respect to a city's livability and sustainability (Figs. 13–16).

These limitations explain why there is so much interest in building a metro in Bogotá. Low- and medium-capacity BRT lines represent the optimal, most economic solution when matched with similar passenger demand. However, a BRT line operating beyond its capacity requires a major investment in a line that provides a higher quality of service, attracts more choice riders, and enhances the city's livability. Bogotá is a city with a steadily increasing population that brilliantly converted uncoordinated midi-bus services into a coordinated network of regular buses and BRT lines. It has used taken advantage of corridors that allowed the four-lane busway, but now must invest in rail transit to further improve its quality of transit service, economic vitality, and sustainability. The question is actually not whether Bogotá's higher-capacity transit system should be BRT or LRT/metro: the city obviously needs both, rail for its most heavily loaded lines, BRT serving a network of medium-capacity lines.

Mexico City's Insurgentes BRT: Similar to Bogotá, the Insurgentes corridor was served by uncoordinated minibuses with erratic, unreliable service. The first 20 km and 36 stations of the Insurgentes BRT facility opened in 2005; in 2008 an additional 9 km opened. As with the TransMilenio BRT system this line operates in the median of a major arterial road requiring passengers to access stops only through one entrance after long walks. Buses stop one at a time and cross many signalized intersections one at a time, so that the maximum capacity obtained using one articulated bus per signal cycle amounts to 5,000–6,000 persons/h.

The BRT line was so much better than the minibuses that the line attracted 280,000 persons/day, which exceeded its capacity and resulted in extreme, sometimes dangerous, overcrowding.



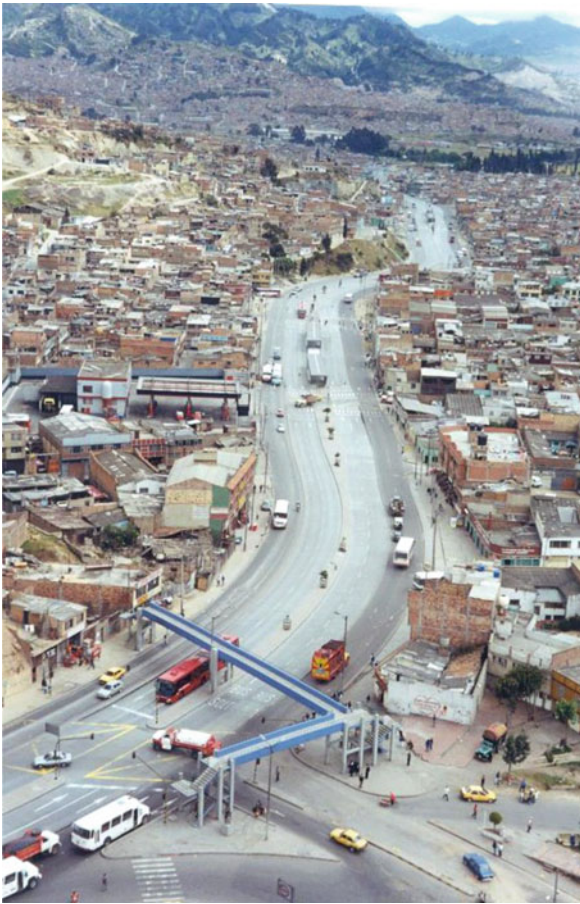
Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 13
Back-up of buses at TransMilenio station reduces service reliability



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 14
Long overpasses are only access to many TransMilenio stations

Also similar to TransMilenio, the Insurgentes line was built faster and at lower investment cost than an LRT line would have required. However, while its current operation can be deemed a success based on its daily ridership, its capacity limit was reached at the

time the line opened. An upgrade to rail technology could allow double or triple the capacity still maintaining only one transit unit (train) per signal cycle through intersections. Only the street block length would limit the potential train length. Safety



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects.

Figure 15

TransMilenio corridor is a major barrier to pedestrians in Bogotá

would also be increased with the decrease in the number of bus braking and accelerating cycles and with the added signal protection on any segment where train speed exceeds 70 km/h. LRT would have provided so much greater capacity, resulting in correspondingly greater riding comfort. Given the present ridership levels, one could argue that conversion to a metro line would even have merit.

The Bogotá and Mexico City examples show fairly typical decisions many cities face as they ponder how to improve their transit services. If there is an avenue in which ROW B can be obtained, BRT usually requires

a lower investment and simpler/shorter implementation. However, LRT would provide a much higher capacity, better riding comfort and passenger attraction over the long term. Moreover, with respect to the city's livability and sustainability LRT is clearly superior to diesel (or even CNG) buses, particularly in sensitive inner city areas.

Istanbul Freeway Median BRT: Istanbul is by any definition a megacity spanning a very large region. Due to the long travel distances and extremely heavy congestion, the traveling public wastes much time. Even the limited access highways can be chaotic with thousands of buses stopping along the roadside, thus resembling ROW C much more than ROW A in character. In 2007, the first 18 km and 14 stations within one such freeway opened as a BRT system (Phase I). Typically, its stops and dedicated lanes were located in the middle of the limited access highway. In 2008, an additional 29 km and 25 stations were added (Phase II). At that time it was projected that an additional 11 km would be built for a total of 50 km at a relatively modest total cost of \$125 M (Fig. 17).

Phases I and II already carry 858,000 passengers per day, and many passengers are saving over 1 h per day in commuting times. Thus, it would seem to be a major success. However, this very success indicates that the conditions are strong for an upgrade to rail technology. There are close to 2,500 bus trips made per day on this busway with headways often down to 20 or 30 s of separation. Consequently, there is a significant amount of air pollution and fuel consumption from the enormous volume of buses. Furthermore, bus speeds and passenger comfort are limited and safety is compromised due to hundreds of thousands of accelerating and braking cycles per day at highway speeds.

The ready availability of the right-of-way and the long station spacings due to their location at overpasses would allow for the running of large high-capacity trains that accelerate faster and obtain higher speeds than do buses. The high demand and ROW A clearly justifies rapid transit technology, not LRT technology. Headways would still be short while time savings and passenger comfort would be greatly increased. Safety would be enhanced by automatic train protection. Total energy consumption and both air and noise pollution would be reduced. Operating cost savings would



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 16
Exhaust pollution from TransMilenio operations



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 17
BRT with ROW category A in Istanbul, Turkey

be substantial and could be used to bolster other parts of Istanbul's network including more feeder services.

It is true that far fewer bus drivers would be needed, but this decrease in employment would be far offset by

the increase in economic vitality and job opportunities opened with the corridor's faster travel times. (There would also be some offsetting employment created to maintain and repair the guideway and vehicles.)

Comparison of LRT and BRT Modes

Light rail transit and bus rapid transit (but not Bus Transit Systems) are functionally similar modes. As semi-rapid transit (mostly independent of street traffic), both provide much higher service performance and have more positive impacts than the basic street transit mode – regular (conventional) buses (RB). Both require investments that are significantly higher than those for RB, but much lower than for metro systems. However, LRT and BRT are drastically different in their technology, operations, quality of service, and their short- and long-term impacts on the city. In most cases, they typically provide different “investment cost/performance packages” so that their comparison is very complex.

Applications of the two modes vary between two extremes. In medium-sized cities or corridors BRT can fully meet the capacity and performance needs at lower cost than LRT. At the other extreme, in many medium- or large-size cities LRT offers far superior performance, operates efficiently in pedestrian-oriented areas or in short tunnels under city centers, and has many more positive impacts for a city’s livability than does BRT. Between these two poles, where BRT and LRT are, respectively, obviously the superior choices, are many applications with different trade-offs so that either one of the two systems may be the preferred mode.

Review of Modal Characteristics

Table 1 presents a comparison of the basic characteristics of RB, as the most widely used street transit mode, BRT and LRT. The characteristics are grouped in three categories: system components, lines and operational components, and system characteristics.

As Table 1 shows, the elements in which BRT differs from RB are ROW category, larger vehicle capacity if double-articulated buses are used, different line designs and stop spacings, higher investment costs, and its greater passenger attraction.

Focusing on the BRT and LRT modes, their comparison can be summarized in a number of characteristics, as presented in the following box [5].

Some of these comparisons are factual and obvious, proven in real-world situations. Several of the major differences will be discussed here.

Advantages (+) and Disadvantages (–) of LRT over BRT

- + Separate ROW (B or A) for LRT is easier to achieve because LRT uses rail tracks instead of roadway lanes, and due to its different technology requires no physical protection and police enforcement, as do busways (Fig. 18).
- + LRT has better vehicle performance than BRT because of its electric traction.
- + LRT produces no exhaust along the line and much lower noise than BRT (except that in a few cities, trains are required to use horns at grade crossings).
- + LRT is often designed to serve as the central element for access and image of pedestrian areas in central cities; a busway with high-frequency bus services is much less compatible with “pedestrianized” areas.
- + LRT can use tunnels, BRT cannot.
- + LRT vehicles are more spacious and comfortable and have better riding quality than buses.
- + LRT has a stronger image; it is more popular and attracts more riders.
- + LRT has a stronger positive impact on urban development than BRT.
- Investment costs for LRT are higher than those for BRT.
- For the first LRT line in a city, introduction of a new technology requires more extensive construction of infrastructure as well as new equipment, and it involves longer implementation.

Diesel Bus Technology Versus Electric Rail Technology

The basic benefits and drawbacks of diesel and electric traction, and rubber-tired and rail technology are inherent in the BRT and LRT modes. All BRT systems use the internal combustion engine for propulsion. In the past the fuel was diesel. Recently, new BRT systems in the industrialized world use less polluting liquid natural gas (LNG) or compressed gas (CNG) as fuel sources, but engine performance does not fundamentally change.

More detailed analysis of BRT and LRT characteristics caused by their different types of traction and

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Table 1
Comparison of regular bus, bus rapid transit, and light rail transit characteristics

Mode► Characteristic▼	Regular bus(RB)	Bus rapid transit (BRT)	Light rail transit (LRT)
System components:			
ROW	C	B (C, A)	B, (A, C)
Support	Road	Road	Rail
Guidance	Steered	Steered	Guided
Propulsion	ICE	ICE	Electric
TU control	Driver/visual	Driver/visual	Driver/signal
Vehicle capacity (spaces)	80–120	80–180	100–250
Max TU size	Single vehicle	Single vehicle	1–4 car trains
Max TU capacity	120	180	$4 \times 180 = 720$
Lines/operational elements:			
Lines	Many	Few	Few
Headways	Long/medium/short	Long/medium/short	Medium/short
Stop spacings (meters)	80–250	200–400	250–600
Transfers	Few	Some/many	Many
System characteristics:			
Investment cost/km	Low	High	Very high
Operating cost/sp	Medium	Medium	Low
System image	Variable	Good	Excellent
Pass. attraction	Limited	Good	Strong
Impacts on land use and city livability	Least	Moderate	Strongest

road/rail technology are given in the following two boxes, respectively [6].

Several relevant points from the above comparisons deserve some discussion here.

- LRT in most cases costs more to construct initially. Although rail equipment and facilities last longer, the required higher initial investment is often a major problem. An exception to LRT costing more than BRT might be where ridership demand requires a category A BRT to avoid at-grade crossings, but LRT can provide that capacity with a less expensive category B design.
- LRT has much more capacity because rail technology allows the coupling of railcars into trains; coupling cannot be done with buses. This is particularly important for transit projects using category B rights-of-way. Traffic engineers limit the amount of green time given to transit. If the expected ridership demand on the line is high, the transit unit used must carry the most passengers. In this regard, LRT has the added advantage of requiring crossing gates for safety.
- BRT has the potential to offer more service options, not just the end-to-end operation typical for LRT. A BRT line can offer end-to-end service, but can



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 18
Recently opened LRT line in Dublin, Ireland on a ROW category A section

supplement it with express bus services or multiple route-to-trunk line services typical of freeway bus operations.

- If capacity and service quality require that ROW A is used, that is usually more complicated for buses than rail vehicles and results in bus services which are much inferior to rail. The best example is the Silverline BRT in Boston, where a 1-mile long tunnel required an investment cost of about \$500 million, and buses now operate in it at speeds limited to 10–25 km/h. Capacity of buses operating in single-lane tunnels is only a fraction of the capacity LRT would provide.
- Road and rail technologies also have a direct impact on operations of their rights-of-way. Separation of ROW for LRT needs no enforcement because in most designs road vehicles cannot use tracks because they are not paved. BRT's advantage, that it uses the same road surface as other street lanes, is actually a serious disadvantage with respect to control of their use. Many bus lanes and busways have been first downgraded by allowing other vehicles to share them (first taxis and vehicles making turns at intersections, then HOVs, any cars who pay tolls in such lanes, and then even hybrid private cars).

In many cases these steps led to eventual losing of ROW B for buses and discontinuation of the BRT system (see Fig. 3).

Electric Rail Traction Compared with the Internal Combustion Engines of Buses

- + Produces higher, smoother acceleration (limited by passenger comfort)
- + Produces far less noise and vibration
- + Produces no local air pollution
- + Can easily use tunnels due to absence of pollution and good dynamic performance
- + Allows for regenerative braking, thus reducing energy consumption
- + Is much cleaner to operate and maintain
- Requires additional investment for electrification of lines and construction of substations
- Overhead power lines are sometimes criticized for aesthetic reasons, although many passengers like the distinct identity the catenary gives the line
- Is susceptible to power failure that stops all vehicles on a section of line

Rail Technology Compared with Rubber-Tired Buses

- + Makes coupling of cars into trains possible, drastically increasing line capacity
- + Rail guidance allows use of wider and longer cars and requires narrower free profile
- + Has much higher safety because of automatic signal control, although at additional investment and maintenance costs
- + Provides a far more stable, smoother ride quality
- + Is far more energy-efficient due to steel wheels on steel rails
- + Can better cope with adverse rain, ice, and snow conditions
- Requires substantially higher investment, although the vehicles and guideways are more durable and require lower ongoing maintenance
- Cannot negotiate as steep a gradient, nor as sharp curves as buses
- Requires a higher degree of safety because of longer stopping distances
- Can be much louder when going through sharp curves
- Is normally slower around any given radius of curvature and may therefore have a slower travel time between stations than bus technology

Line Capacities

An extensive debate has been going on with respect to the line capacity of different transit modes. To check the validity of various claims of modal capacities, two values will be quoted for each mode: the first, for the bus mode, assumes regular buses with 90-space capacity (6 persons/m²) and with single stops with fast boarding/alighting, allowing average headways as short as 1 min. Such a system provides a line capacity of 5,400 spaces/h.

The second value for bus line capacity assumes that each stop has four lanes, allowing overtaking and “leap-frogging” of buses. In this way, capacity can be increased significantly. This is seldom possible in urban areas, but some examples exist. Portland, Oregon, organized a pair of bus streets with two lanes for buses and overtaking of buses in stop areas, which

achieved capacity of 180 buses/h or average headways of only 20 s. With an average capacity between regular and articulated buses of 110 spaces, this results in a line capacity of 19,800 spaces/h.

The Comonor project, a high-capacity bus corridor in São Paulo, Brazil, claimed to have achieved capacity of 24,000 spaces/h by operating buses in platoons overtaking each other at stops along the line. However, that description turned out to be theoretical, and actual capacity provided on São Paulo streets was considerably lower.

New claims of much higher capacities for new BRT systems came particularly with the opening of the TransMilenio system in Bogotá, Colombia. That system was systematically designed for high capacity: most buses are articulated and double-articulated, all fares are collected at station entrances, and the system has two lanes on some sections, but four lanes in station areas allowing bypassing and overtaking of buses. This is particularly the case on the main line built in a wide median of a very wide freeway right-of-way. However, the line has a number of signal-controlled intersections, which limit the green time for the BRT line.

Even if it is assumed that all buses are double-articulated and occupied with an extremely high average density of 6 persons/m², and that it is possible to have an average headway of buses crossing signalized intersections of 20 s, such an operation would amount to about 28,000 spaces/h. Although these assumptions are higher than in real world (for one, not all buses are double-articulated), advocates of BRT systems have claimed capacities exceeding 30,000, later 35,000 and even as high as 53,000 persons/h. The latest revisions to a couple of prominent BRT design manuals written for applications to developing countries appear to be correcting these overblown numbers downward, toward lower, although still unrealistic values of over 30,000 persons/h.

For comparison, the capacity of LRT lines operated with trains consisting of two articulated cars (such as in Manila) with realistically achievable 2-min headways is about 15,000 spaces/h. With more optimistic assumptions, corresponding to those used by BRT promoters, LRT lines using four-articulated car trains as operated in several cities and 1.5 min headways would achieve an offered capacity of 32,000 spaces/h. With four tracks for bypassing in stations, this capacity could be

increased further, but the critical locations would be at intersections. As the measurements of actual operations of the Orange Line BRT (Los Angeles) show, LRT can provide substantially higher capacity at street crossings than buses because of the higher capacity of LRT trains compared to individual buses, even double-articulated ones.

Under similar assumptions, ten-car trains of a metro system operating at 1.5-min headways would provide a capacity in the order of 60,000 spaces/h, while the four-track metro line in New York carried 89,000 persons/h in the 1940s (presently, passenger numbers are smaller, because trains in most of the industrialized countries are operated with higher comfort levels which result in 4–5 persons/m²).

Another deceptive feature of these claims of BRT capacities is that they represent the obsolete, simplistic measure of line capacity as a single number, without regard to service quality and level of service. With respect to highway capacity, it was already in 1950 realized that capacity in terms of vehicles per hour should be related to the level of service (LOS), which was defined as LOS A through F. Capacity of transit lines is now also related to performance and LOS. For example, if one transit line carries 14,000 persons/h with an operating speed of 16 km/h and another line carries 14,000 with a speed of 24 km/h, their performance is by no means the same. Lehner [7] introduced the concept of productive capacity – product of transporting capacity and speed – to include this characteristic. It can be insightful to plot the productive capacity against investment cost. Vuchic [8] specified that evaluation of transit capacity should include the following five factors:

- Offered line capacity in spaces/h
- Operating speed in km/h
- Load factor or capacity in persons/space, where spaces include both seated and standing spaces assuming a certain degree of crowding
- Comfort standard in square meters/person (or degree of crowding in persons/m²)
- Reliability of service in percent of departures on time

Consequently, capacity of transit modes cannot be evaluated only by hourly throughput of persons; it must include level of service.

Comparisons of capacities of different modes must also be made for comparable conditions and assumptions. For example, comparing capacities of BRT and LRT must assume that both modes have either two lanes/tracks, or four lanes/tracks in stations. Thus, the Insurgentes BRT line in Mexico City should be compared with a two-track LRT line, such as in Cologne or Manila. The TransMilenio BRT line in Bogotá should be compared with a four-track LRT line, which would have capacity well over 40,000 spaces/h.

Compared modes must also have the same load factors and comfort standards. Reliability and operating speed would then have to be measured or predicted on the basis of characteristics of each mode.

Recent Studies Comparing Different Modes of Real-World Transit Systems

Studies comparing transit modes generally fall into two categories. The first compares modes that are being planned or hypothesized, that is, not in operation. These types of studies are needed, of course, when doing major planning work, but they must use projections of ridership and costs rather than actual ridership and costs. The alignments and operational assumptions made for each alternative should be as similar as the characteristics of different modes allow.

The second category of studies compares modes operating in one or more cities. A major problem with these types of studies is that each system operates in a different cultural, economic, and operational context, but their great advantage is that their features and numerical values are realistic, not hypothetical and subjective.

One recent study that looked at one city with several bus and rail modes operated by a single agency is described below.

Case Study: Comparison of Transit Modes in Los Angeles Over the past 25 years Los Angeles' metro transit network has evolved from an all-bus system to a network of many transit services and modes. As of spring 2008, this network included a rapid transit line, three light rail lines, three busways, 19 enhanced bus transit routes, and 95 local bus routes. For the first time the opportunity exists to compare a variety of transit modes all operated by the same agency within the same

urbanized area eliminating differences in labor costs between urban areas, in operating and management practices, in efficiencies of scale, and in time and methods of data collection [9].

Various performance and cost measures were calculated for each mode operated by the Los Angeles metro. The results of this analysis are shown in Table 2 for performance measures, in Table 3 for cost measures.

The Orange (BRT) Line is much slower than the average of the LRT lines. This is because it does not have full signal priority and catches red lights at a third of its intersections. Its buses must also slow below 32 km/h (20 mph) at all crossings. It also has nowhere near the carrying capacity of the light rail lines and is nearing capacity with about 25,000 daily riders. One LRT Line (Blue) has had a weekday ridership above 80,000 for a number of years.

On the other hand, the Orange Line was built for less than half of the capital cost per kilometer of the Gold (LRT) Line during the same period. Time will tell whether that investment was prudent given the much slower speed and the looming capacity limit of the busway. The Orange Line may be an example of a BRT line that should have been built fully grade-separated for higher speed and capacity, but if it had been, its cost might have exceeded the cost of an equivalent light rail line operating on the existing ROW B.

Summary Comparison of BRT and LRT Modes

Table 4 gives a summary comparison between the BTS, BRT, and LRT modes. Overall, the two bus modes have advantages with respect to investment cost, construction time, and the complexity of system implementation. However, LRT demonstrates superiority in most measures of service efficiency and level of service: speed, comfort, image, and passenger attraction. Even more important may be that LRT is superior in its positive impacts on land use planning, urban form, livability, and sustainability. Focusing on the BRT-LRT comparison, BRT tends to be a faster and usually (but not always) lower investment solution, but LRT provides higher service quality, stronger passenger attraction, and a more powerful step in increasing the city's quality of life and sustainability.

Trends and Expected Future Directions

City populations in many developing countries are growing rapidly. Those countries that also have growing economies and rising income levels are seeing ominous growth in auto ownership. One defense against the inevitable, debilitating congestion that these new cars bring is to invest in attractive urban transit systems capable of meeting future demands.

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Table 2
Performance measures of Los Angeles metro transit modes (2008)

Performance measure	Local bus	Rapid bus	Orange Line BRT	Light rail	Rapid transit
Ave. peak hour speed (km/h)	20.6	24.0	29.3	41.4	51.8
Ave. trip length (km)	5.7	7.3	9.4	11.3	8.0
Daily riders: (experienced) (possible max)	30,000 30,000	30,000 30,000	25,000 35,000	84,000 100,000	140,000 300,000

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Table 3 Cost measures of Los Angeles metro transit modes (2008\$ unless noted)

Cost measures	Local bus	Rapid bus	Orange Line	Light rail	Rapid transit
Capital cost (\$M/km)	N/A	\$ 0.15 (2000)	\$17.3 (2005)	\$ 38.9 (2003)	\$130 (2000)
Operating cost per pass-km	\$0.60	\$0.39	\$0.30	\$0.31	\$0.27
Operating subsidy per pass-km	\$0.47	\$0.29	\$0.22	\$0.25	\$0.20

Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Table 4
Summary comparisons of the BTS, BRT, and LRT modes

Mode characteristic	Bus transit system BTS	Bus rapid transit BRT	Light rail transit LRT	Superior mode
Investment cost	Medium	High	Very high	BTS
Implementation Complexity and time	Short	Medium	Long	BTS
Operating cost	Lower for low passenger volumes	Lower for low passenger volumes	Lower for high passenger volumes	Depends
Operating speed	Medium	High	High	Depends
Ability to accommodate service options	Low	Some with four-lane stops	Low except with four-track stops	BRT
Capacity	Low	Medium	High	LRT
Type of energy and traction	Internal comb. engine	Internal comb. engine	Electric	LRT
Vehicle performance	Good	Good	Excellent	LRT
Air pollution and noise	Poor	Poor	No local pollution, low noise	LRT
System image and passenger attraction	Fair	Good	Excellent	LRT
Potential to influence land development	Limited	Fair	Very good	LRT
Contribution to livable urban environment	Some	Limited	Excellent	LRT

For large cities with many million inhabitants, high population densities, and heavily traveled corridors, rail rapid transit (metro) is clearly the most efficient transit mode for the basic network. Megacities like Tokyo, Beijing, and São Paulo will have to extend their metros as the population continues to grow.

The trend of developing medium-capacity modes, which started with the growth of LRT and later BRT, will continue. These modes are being introduced to supplement metros in suburban areas and as transitional solutions when metros cannot be built fast enough for financial or physical reasons.

The two modes most capable of meeting the need in many cities in developing countries are LRT and true BRT. Both, however, are costly investments. One future direction is therefore to convey to transit policymakers that the investment decision they face is between these two modes, not the false promise of inexpensive, inadequate lower-cost bus modes.

In developed countries, a future direction for study is to appraise honestly the cost and performance of true BRT systems and their more comprehensive service options. In some applications the LRT model of a high-capacity rail line fed through transfers from connecting bus routes may not provide the most attractive, convenient service. In other cases, if a BRT would be loaded to capacity as soon as it is opened (which is the case with some lines in Bogotá and Insurgentes in Mexico), a rail system – LRT or metro – would obviously be a more efficient and permanent solution. Understanding where each of these options works best will be quite useful.

Finally, the damaging argument within the transit community between BRT and LRT must subside if transit is to compete most aggressively with the private car. In a world that needs to have far fewer private cars depleting our oil reserves, strangling our cities, and fouling our air, the focus must be to provide the most



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 19 Five-section low-floor LRT vehicle provides high capacity and can make sharp turns on ROW category B in urban streets in Helsinki, Finland



Bus Rapid Versus Light Rail Transit: Service Quality, Economic, Environmental and Planning Aspects. Figure 20 Buses and light rail trains share ROW category B in Helsinki

attractive, cost-effective transit, bus, or rail for a given circumstance. It should not be to have one mode to the exclusion of another. A good example for this is Bogotá, where the debate should not be BRT versus LRT, but BRT *and* a rail system (LRT or metro). This is

particularly the case with lines where volumes are very high and environmental aspects are very important. In such cases the transit system must enhance the livability of the city, minimize its air and noise pollution, and join rather than divide its neighborhoods (Figs. 19 and 20).

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Bus Versus Rail Implications for Transit-Oriented Development

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Glossary

BRT Bus rapid transit (BRT) refers to a variety of mass transit systems that utilize buses to provide faster, more efficient services than a conventional bus line. BRT runs on existing roadways or dedicated rights-of-way and offers such operational features as high-capacity, low-floor bus vehicles, traffic signal prioritization, and real-time information services.

LRT Light rail transit (LRT) refers to electrically propelled rail vehicles operating singly or in trains. It obtains power from overhead cables and runs on reserved but not necessarily grade-separated rights-of-way. LRT provides service capacities and speeds typically lower than metro rail.

Metro rail Metro rail typically consists of steel-wheeled, electric-powered vehicles operating in trains of two or more cars on a fully grade-separated right-of-way. Alternative names for metro rail include subway and heavy rail. It offers higher capacities and speeds than light rail.

New urbanism New urbanism refers to an urban design movement led by a group of architects and urban planners in the USA since the early 1980s. New urbanism promotes walkable neighborhoods and attacks suburban sprawl through nonconventional physical planning and design approaches. Traditional neighborhood design (TND) and transit-oriented development (TOD) are two examples of new urbanist practice.

TOD Transit-oriented development (TOD) refers to mixed-use, medium- to high-density development around the transit station with pedestrian- and cyclist-friendly environmental design. The term was coined by Architect Peter Calthorpe while other terms, for example, Transit-Focused Design and Transit Villages, have also been used to describe similar development concepts.

Transit ridership The quantity of passengers riding on the transit over a given period of time, for instance, a day or a year.

Transit value capture Transit value capture refers to the process by which all or a portion of increments in land value attributed to public transit investments are recaptured by the public sector. The idea can be traced back to the thinking of Henry George and his followers. The rationale states that transportation projects improve accessibility to the adjacent land. This improved accessibility is capitalized in property values, generating a windfall for private landowners. Public agencies can capture a portion of that windfall by utilizing a variety of methods. The captured value can then be used to finance transportation or other public infrastructure.

VMT Vehicle miles traveled (VMT) measures the distance in miles that vehicles are driven over a given period of time, for instance, a day or a year.

Definition and Importance

Transit-oriented development (TOD) refers to mixed-use, medium- to high-density development around the transit station with pedestrian- and cyclist-friendly environmental design oriented to transit services. Integrating transit with land use has been a common practice in most European, Asian, and Latin American cities. It is not a brand-new idea in the USA either. In the streetcar era, for example, developments largely concentrated along transit corridors in Boston, Chicago, San Francisco, and many other streetcar communities. TOD began to regain popularity in the early 1990s when the US Architect Peter Calthorpe coined the term in his book *The Next American Metropolis: Ecology, Community, and the American Dream* [1]. Other terms have been used by transportation professionals, urban planners, and the real estate industry to express similar development concepts, for example, “transit-sensitive land use” [2], “transit-oriented design” [3], “transit-focused development” [4], and “transit villages” [5]. TOD represents these multi-professional interests in developing around transit. Amid a worldwide trend of rising motorization and growing vehicle miles traveled (VMT), TOD is being widely promoted as a strategy to achieve sustainable transportation. Currently, there are over 4,000 transit sites in the USA offering significant potential to practice TOD [6].

At the center of TOD is transit. There are a variety of transit technologies; broadly they can be grouped as bus-based or rail-based. Bus- versus rail-based transit presents distinctive operational and service characteristics and involves quite different levels of public investments. Accordingly, bus-TOD versus rail-TOD entails different planning and design considerations. Whether to develop bus- or rail-based mass transit has long been a topic of policy debate. Recent developments in bus rapid transit (BRT) and light rail transit (LRT) throughout the world add to existing heated discussions on the advantages of bus- versus rail-based transit systems. This entry describes the comparative characteristics of bus- versus rail-based transit and discusses their implications for TOD.

Introduction

Transit-oriented development (TOD) is a strategy to integrate transportation with land use by focusing development on transit. A number of factors have motivated many communities in the USA to pursue TOD. Fighting sprawl and sprawl-induced problems is among the top. Community development in the USA after World War II can be largely characterized as low-density, strictly separated land uses, and car-oriented design. In a sprawling built environment, transit becomes operationally unviable and driving becomes a necessity. The consequences are ever-growing vehicle miles of travel (VMT) and increasing roadway congestion, energy consumption, and vehicle emissions. TOD offers potentials to curb sprawl and to help reduce the driving-related problems. Many state and local governments are encouraged to implement TOD by the recent steady increase in federal funding for transit. For example, the three transportation bills in the less than 20 years, namely, ISTEA to TEA21 to SAFETEA-LU, authorized increase in transit funding from \$25 to \$36 to \$52.6 billions, respectively.

TOD is being widely advocated in Europe, Asia, and Latin America as well although their cities have traditionally developed in relatively high densities and rich mixed uses. The TOD interest grows out of the concern that new developments in many of these cities tend to depart from the traditional urban form. Amid rising income and associated growth in private motorization, neighborhoods and workplaces are becoming

increasingly car oriented and pedestrian/cyclist hostile. Densities in these cities are high relative to the North American cities; yet the high density may not function well if it is not fully integrated with the transit. Dysfunctional density likely leads to what the New Urbanist Andres Duany called “high-density sprawl” [7]. Careful TOD planning, design, and implementation are essential for transit and its surrounding built environment in order to benefit from density.

A TOD typically has five attributes: transit access, a district of walking distance from the transit, mixture of different compatible urban functions, medium to high development density, and pedestrian- and cyclist-friendly environmental design in the TOD district. These attributes are interrelated and their composition for a specific TOD will vary by the spatial, socioeconomic, and technological context in which the TOD is proposed. TOD planners have created TOD typologies, specifying variations in design attributes for TODs in different spatial context, for instance, downtowns, urban neighborhoods, employment centers, and other regional locations [8]. As transit is at the center of TOD, TOD attributes will also vary by transit technologies.

Transit Technologies

Transit technologies evolve along with advances in vehicle technologies, information and communications technologies, as well as power and energy technologies. Table 1 shows the most commonly seen urban transit modes grouped into two categories: bus-based and rail-based. A comprehensive list and characterization of urban transit can be found in Vuchic [9].

TOD attributes and the ways in which these attributes interact will differ depending on the specific transit that the TOD is proposed for.

- A particular type of transit technology is associated with certain levels of cost. In general, the cost consists of two parts: capital and operation. Capital costs include vehicle cost and infrastructure cost (land acquisition and clearance and system complexity). Operating cost includes labor, insurance, fuel, administration, and others.
- Different transit technologies and operating plans deliver various levels of service capacities. Main

Bus Versus Rail Implications for Transit-Oriented Development. Table 1 Transit technologies and descriptions

System technology and description	Example systems	Service geography	Average speed	Station spacing	Typical headway	Guideway	Typical power source
Bus-based							
<i>Regular bus:</i> A road vehicle designed to carry multiple passengers. Buses vary in capacity from a dozen to several hundred passengers.	Cities with transit services	Urban	15–30 km/h	0.2–1.0 km	8–20	On street	Gasoline
<i>Trolley bus</i> A passenger <i>bus</i> operating on tires and having an electric motor that draws power from overhead wires.	New Orleans	Urban	15–30 km/h	0.2–1.0 km	8–15	On street	Electric
<i>Bus rapid transit</i> BRT is a relatively new umbrella term for urban mass transportation services utilizing buses to perform premium services on existing roadways or dedicated rights-of-way.	Pittsburg, Curitiba, Bogota, Beijing	Urban, Regional	25–50	0.4–1.5	10–20	Shared or exclusive ROW	Gasoline
Rail-based							
<i>Streetcar</i> Bus on rails typically operating on city streets	Portland	Urban	15–25	0.4	8–15	On street	Electric
<i>Light rail</i> With an overhead power supply and LRT utilizes predominantly reserved but not necessarily grade-separated rights-of-way. Electrically propelled rail vehicles operate singly or in trains. LRT provides a wide range of passenger capabilities and performance characteristics at moderate costs.	Dallas: DART; Denver:	Urban, Regional	30–60	1–1.5	5–30	Exclusive or shared ROW	Electric
<i>Heavy rail</i>	Washington, D.C. Metro; San Francisco: BART; New York City: MTA Boston: MBTA Chicago: CTA	Urban, Regional	80–130 km/h	1–3	3–10	Grade-separated, Exclusive ROW	Electric

Bus Versus Rail Implications for Transit-Oriented Development. Table 1 (Continued)

System technology and description	Example systems	Service geography	Average speed	Station spacing	Typical headway	Guideway	Typical power source
<i>Commuter rail</i>	Boston Purple Lines: MBTA; New York Long Island Railroad San Jose: CalTrain	Regional	50–120 km/h	3–10 km	15–30 min.	Exclusive ROW	Diesel or hybrid

B

factors affecting service capacities include vehicle size, service frequency, and road conditions.

- Carrying capacity, along with other operational and contextual factors, determines the level of services (LOS). Existing empirical studies have shown that the extent of land-use impacts of transit development is positively associated with LOS. In other words, higher capacity systems such as metro likely have stronger positive impacts on the value of land near the station.
- More expensive land leads to higher development intensity, which will result in higher population or employment density.
- Higher population and job density provides a larger pool of transit ridership. If there are more people riding on the transit, farebox revenue will increase. Higher density also provides a larger basis for economic activities and a larger tax base for the local community. The farebox and tax income help reduce cost burden of building and operating transit systems. Ridership increases, however, may trigger a greater need for expanded services, which can lead to increases in operating and potentially capital costs.

Cost Characteristics of Bus Versus Rail Mass Transit

The main topic of debate on bus versus rail transit development is cost. Recent discussions largely focus on cost comparisons between BRT and LRT due to a number of performance similarities between them. On a per user basis, rail transit systems generally cost more to build than bus transit but less to operate owing to relatively higher capacities associated with rail. Still, within each type of transit, there are large variations in technical specifics and operational characteristics.

Capital Cost Comparison Between Bus and Rail Transit

Table 2 shows the average capital cost per route mile for BRT, LRT, and MRT based on selected systems reviewed by USDOT [10], GAO [11], and BAH [12]. On average, BRT costs \$10.24 millions (in 1990 dollars) per mile to build, less than half of LRT (\$26.4 million) and less than one-tenth of MRT (\$128.2 million). Nevertheless, average cost-based comparisons between bus and rail will likely generate controversies [13]. Table 2 also shows the ranges of capital costs of the transit systems studied. Notably, within same type of transit technology, capital costs vary considerably. For instance, the BRT in Miami, FL costs \$5.6 million per mile to build, whereas the West Busway BRT in Pittsburgh, PA costs \$41.7 per mile, higher than the average capital cost of LRT. The most expensive LRT among the 21 projects reviewed by USDOT [2] is in Buffalo, NY, which costs \$90.19 per mile, over 40% higher than the per-mile capital cost of the metro in Miami.

Many factors contribute to the large variations in the capital costs of transit systems. Costs of BRT projects, for example, include vehicles (regular or articulated), the roadway cost (busways or bus lanes), station structures, park-and-ride facilities, communications, and traffic signal systems. For rail transit systems, guideway elements may take a large share of capital costs, depending on types of structure (e.g., tunnel or elevated). Different ways of accounting the costs by including (or excluding) various capital cost elements will change the average cost figures quite significantly. Hence, when comparing different types of transit systems with respect to capital costs, it is important to maintain consistency in cost reporting

Bus Versus Rail Implications for Transit-Oriented Development. Table 2 Capital cost comparisons of bus versus rail (in 1990 US\$)

	BRT	LRT	MRT
Average cost per route mile (millions)	\$10.2	\$26.4	\$128.2
Cost range (millions)	\$5.6 ~ \$41.7	\$9.4 ~ \$90.2	\$63.9 ~ \$169.6
Number of projects reviewed	9	21	4

Sources: Calculated from [10–12]

Bus Versus Rail Implications for Transit-Oriented Development. Table 3 Per mile capital cost breakdown of bus versus rail (in 1990 US\$1,000s)

	BRT		LRT		MRT	
	\$	%	\$	%	\$	%
Land (right-of-way)	3,018	15.0	1,520	7.8	7,436	5.8
Guideway	6,495	33.5	4,289	22.0	33,333	26.0
Trackwork or special conditions	983	8.5	1,686	8.7	5,385	4.2
Stations	1,387	9.1	1,094	5.6	33,333	26.0
Power and control	113	2.7	2,047	10.5	10,513	8.2
Facilities (yards and shops)	192	1.9	974	5.0	2,820	2.2
Eng./Mgt./Test (soft costs)	2,948	20.3	5,581	28.6	19,230	15.0
Vehicles	1,483	9.0	2,295	11.8	16,154	12.6
Total	16,620	100	19,486	100	128,203	100

Sources: Calculated from [10–12]

and to examine/compare specific cost elements whenever data is available. Such itemized comparisons allow clear identification of specific factors driving up the system development cost.

Table 3 shows the breakdown of capital cost by subsystems for the three types of rapid transit technologies. Data for LRT and MRT come from a USDOT study of nine completed projects [2], whereas cost data for BRT are for two proposed systems in Atlanta, GA and Albuquerque, NM. Note that, although BRT costs less on average than LRT (\$16.6 and \$19.5 million per mile, respectively), for several items BRT costs exceed those of LRT. For instance, the average land acquisition cost (right-of-way) for the BRT projects (\$3.018 million per mile) is almost twice as much as that of LRT project (\$1.52 million per mile). This is partly because BRT requires a wider right-of-way than

LRT. BRT guideway cost (\$6.495 million per mile) is much higher than that of LRT (\$4.289 million per mile) due to construction of dedicated busways. Station cost for BRT is also slightly higher than that of LRT. In most cases, a BRT station is located in highway median areas and requires elevated structure for passengers to access the station from both sides of the road. Capital cost for conventional bus is not reported here because it runs mostly on existing roadways free-of-charge and does not require guideways.

Operating Cost Comparison Between Bus and Rail Transit

Table 4 below compares operating costs between the bus and the rail transit modes. Cost per vehicle revenue mile measures the average cost of operating individual vehicles. It is the annual cost of operating a vehicle

Bus Versus Rail Implications for Transit-Oriented Development. Table 4 Operating costs (1990\$)

	BUS	BRT	LRT	MRT
\$ per vehicle revenue mile	3.1	3.6	9.3	6.5
\$ per vehicle revenue hour	45.0	78.8	125.0	152.0
\$ per 1,000 place mile	60.0	72.3	96.0	49.2
\$ per 1,000 passenger mile	616.4	496.9	578.0	282.0

Sources: Calculated from [10, 11]

divided by the total annual number of miles traveled while the vehicle is in revenue service (e.g., excluding the miles traveled to/from the maintenance yard). Among the four transit modes listed in the table, LRT exhibits the highest cost at \$9.3 per vehicle revenue mile. MRT has a relatively lower cost than LRT mainly because it can operate with as long as ten or more cars per train. Standard bus and BRT have the lowest vehicle-mile costs. Operating cost per vehicle hour is another way of measuring the cost of transit operation regardless of the number of passengers carried. MRT, which typically operates at a higher speed than other transit modes, displays the highest vehicle-hour cost. BUS and BRT once again rank the lowest in operating cost measured on the per vehicle revenue hour basis.

The other two measures of operating costs – cost per thousand place mile (where places account for total number of seats and permitted standings) and cost per thousand passenger mile – take into consideration the differences in vehicle capacity and system usage among the transit modes. Notably, MRT has the lowest cost at \$49.2 per thousand place mile, whereas LRT's place-mile cost is the highest at \$96. If usage is considered, BUS has the highest cost at \$616.4 per thousand passenger mile. Again, MRT is the least expensive at \$282 per thousand passenger mile. It should be noted that figures for BRT in the table above are derived from data in the GAO study [3]. The study does not report cost per passenger mile. The figure of BRT's \$496.9 per thousand passenger mile was estimated based on the assumption that average trip distance of BRT passengers was half of the BRT route length.

Overall, figures in the table above indicate that BRT outperforms LRT in all of four operating cost categories. Nevertheless, cautions should be exercised when interpreting these averages. Tennyson [13] has

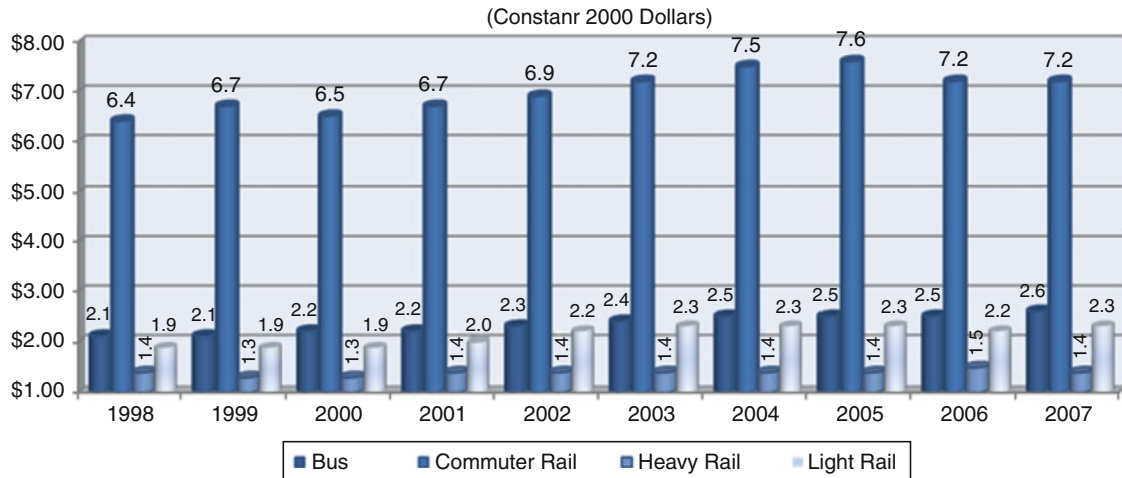
challenged that GAO's study was unevenly biased against LRT – the bus costs were reported too low due to possible inconsistency and errors in the reported data. As with the capital costs reviewed earlier, a wide range of figures exist in each of the four operating costs. The use of alternative measures may give different results on the cost performance of bus versus rail. Operating costs for light rail systems vary widely depending upon the system operating environment [14]. For example, operating costs in Buffalo were \$67 million dollars a year for an on-street system and \$87 million dollar/year for an in-tunnel system [5]. The cost per average weekday boarding on Los Angeles's Orange LRT line is \$16,743 and \$45,762 for the Gold Line Extension [15].

The US National Transit Database reports that, between 1998 and 2007, the operating cost per unlinked trip has increased for all but MRT (Fig. 1) [16].

Capacity of Bus Versus Rail Transit

Bus and rail transit technologies differ in their design capacities. Under different system operational plans, their trunk line capacities may vary significantly. Table 5 provides a reference to the line capacities of standard bus, BRT, LRT, and MRT [17]. The basic capacity of a standard bus serves as a benchmark for line capacity comparisons among these transit modes.

Standard buses can operate in short headways with relatively high frequencies. Unit capacity may vary depending on the bus seating configuration and comfort standard. On average, standard buses can achieve a line capacity of 3,800–5,400 places per hour. Articulated buses have vehicle capacities approximately 50% greater than standard buses. Operating in slightly longer headways and lower frequencies than standard buses, articulated buses can offer a line



Bus Versus Rail Implications for Transit-Oriented Development. Figure 1

Trends of operating cost per unlinked passenger trip for bus and rail modes 1998–2007 [16]

Bus Versus Rail Implications for Transit-Oriented Development. Table 5 Maximum line capacities of transit modes

Mode	Vehicle dimensions (L × W m)	Transit unit capacity (Seat + standing spaces)	Minimum headway (s)	Maximum frequency (Transit units per hour)	Line capacity
Standard bus	12.00 × 2.50	75	70–50	51–72	3,800–5,400
Articulated bus	18.00 × 2.5	120	80–60	45–60	5,400–7,200
High-capacity bus (BRT)	22.00 × 2.50	160	30–12	120–300	9,000–30,000
LRT (partially separated ROW)	24.00 × 2.65	3 × 170 = 510 or 2 × 280 = 560	150–75	24–48	12,200–26,900
MRT	21.00 × 3.15	10 × 240 = 2,400	150–120	24–30	67,200–72,000

Source: [17]

capacity between 5,400 and 7,200 places per hour. High-capacity buses are used by many BRT systems in the world. Examples include Sao Paulo and Curitiba, Brazil, and Transmilenio in Bogota, Colombia. They can achieve a line capacity level more than four times the basic bus capacity. Sao Paulo, Curitiba, and Bogota operate high-capacity buses along well-planned bus corridors. Special operating features such as bus convoys and off-board fare collection allow a total throughput of about 300 buses per hour. At such a high frequency, line capacities were reported to

achieve 24,000 and 30,000 places per hour in Sao Paulo and Bogota, respectively.

LRT line capacities are close to those attained by high-capacity BRT at 4.2 times that of basic bus capacities. An LRT with fully separated ROW will achieve line capacities higher than figures provided above. MRT systems have a great diversity of features that determine MRT line capacities. For instance, dimensions of metro cars in Paris (15.00 × 2.5 m) are much smaller than in Toronto and Hong Kong (21.00 × 3.23 m). Maximum train lengths also vary,

from four cars in Boston to ten or more cars in New York, Tokyo, and San Francisco. In these cities with large-profile systems, line capacities often exceed 70,000 places per hour.

Table 5 provides a reference of transit line capacities under design conditions. In reality, the capacities of these transit systems vary dramatically due to such factors as operational techniques, facility constraints, transit demand, and road conditions. Current debate on BRT-LRT capacity comparisons centers around methods where these constraints are taken into consideration. For example, the communication-based train technology (CBTC) creates very small virtual blocks to allow trains to approach one another in closer intervals. CBTC can increase capacity by 10–15%. Automatic train operation is an operating technology that allows the train to optimize speed, which can increase line capacity by 2–4%. Another factor differentiating the line capacities of bus from train systems is the number of lanes. Typically, BRT travels in a single lane per each direction, whereas rail can follow multiple track lanes. For example, New York has several three- and four-track trunk lines.

Like cost variations, bus and rail transit each offers a wide range of service capacities. Generally speaking, rail transit offers larger capacities than bus transit. In real-world applications, however, it is common to see an overlapping range of capacity offerings by bus and rail transit systems. For instance, BRT in Curitiba achieves far greater higher capacities than the LRT in Buffalo. Vehicle technologies, operation/management efficiencies, and station/street conditions all have significant effects on achievable capacities. Table 6 shows the range of peak-hour capacities suggested by the literature for four aggregated transit modes [18].

Transit Impacts on Property Values

Analyzing rail transit's effects on land use/land development can be built upon the urban location theories, which suggest, in a most succinct form, that transportation defines the urban spatial access pattern and accessibility determines the worth of land. In making location decisions, households (or firms) bid for locations by trading housing (and/or land) consumption against commuting costs to the urban center (e.g., the CBD). The closer to the center, the better the access, and the higher the bid rent. Therefore, we would expect a downward sloping accessibility curve from the urban center. Parallel to the accessibility curve is a downward gradient bid-rent curve. Measuring price or rent levels associated with the proximity to rail transit will provide quantified information on the *magnitude* of rail transit's influence on land value and land use.

Research on property/land value impacts of transit has accumulated a large volume of literature. A number of meta-studies have been published [19, 20]. RICS [19] reviewed about 150 references in the topical area. Most of those reviewed are studies from the USA, Canada, the UK, and Europe. Residential properties have been the focus of the existing studies, while commercial, retail, and office properties were also examined.

Table 7 compiles findings of the reviewed studies of transit impacts on property values. Due to differences in methods used in the studies, direct comparisons of the study findings are quite challenging. This entry groups the studies by property types (residential, commercial, or others) and by transit technologies. The focus is on the magnitude of transit proximity effects measured in monetary terms. Due to limited

Bus Versus Rail Implications for Transit-Oriented Development. Table 6 Capacity comparison among transit modes

	BUS	BRT	LRT	MRT
Typical peak-hour capacity	1,000–3,000	2,000–10,000	3,000–18,000	13,000–41,000
Ratio to BRT capacity	0.35	1.0	1.65	5.3
Highest observed in the USA or Canada	3,000	11,000	10,000	50,000

Source: [18]

Note: (1) The BRT mode shown here combines those mixed with street traffic and those with dedicated busways. (2) BRT is used for ratio calculation is for consistency with cost comparison shown in previous section.

Bus Versus Rail Implications for Transit-Oriented Development. Table 7 Transit impacts on property values

Study	Transit system	Findings	Standardized proximity premium in present US\$	Standardized proximity premium in 1990 US\$
Apartment (monthly rent in dollars per square meters for every meter closer to the station)				
Rodriguez and Targa (2004) [21]	BRT: Bogota	6.8–9.3% increase for every 5 min walk closer to the station; or in 2002 US\$439–653/0.1 km	0.07	0.05
Cervero and Duncan (2002) [22]	LRT: LA County	No significant effects found	0	0
Cervero and Duncan (2002) [23]	LRT: San Diego	East line: within 1/2 mile; 2000 \$104,827 more than other locations	0.27	0.21
Benjamin and Sirmans (1996) [24]	MRT: Washington, D.C.	Rents decrease by 2.4–2.6% for each one-tenth mile increase of distance from a metro station. 1992 mean month rent \$797	(1.24)	(1.15)
Single-family homes (dollars per home for every meter closer to the station)				
Munoz-Raskin (2006) [25]	BRT: Bogota	In most cases, negative impacts are reported for properties location within 5-min distance to the system		
Landis et al. (1995) [26]	LRT: San Diego Trolley	The typical home sold for 1990 \$272 more for every 100 m closer to a light rail station.	2.72	2.72
Landis et al. (1995) [26]	LRT: Sacramento	No effects found	0	0
Landis et al. (1995) [26]	LRT: San Jose	The typical house was worth \$197 less for every 100 m it was closer to light rail.	(1.97)	(1.97)
Al-Mosaind et al. (1993) [27]	LRT: Portland MAX, Eastside	The typical house sold for \$663 more for every 100 ft nearer a light rail station.	21.74	24.02
Chen et al. (1998) [28]	LRT: Portland MAX, Eastside line	Beginning at a distance of 100 m from the station, each additional meter away from decreases average house price by 1992 \$32.20.	32.20	30
Dueker and Bianco (1999) [29]	LRT: Portland MAX, Eastside line	Median house values increase at increasing rates as move toward an LRT station. The largest price difference (1990 \$2,300) occurs between the station and 200 ft away.	37.70	37.70
Lewis -Workman and Brod (1997) [30]	LRT: Portland MAX, Eastside line	On average, property values increase by \$75 for every 100 ft closer to the station (within the 2,500 ft–5,280 ft radius).	2.25	1.83
Knaap et al. (1996) [31]	LRT: Portland MAX, Westside line	The values of parcels located within ½-mile of the line rise with distance from the lines, but fall with distance from the stations.		
Landis et al. (1995) [26]	MRT: BART	1990 single-family home prices decline by \$1–2 per meter of distance from a BART station in Alameda and Contra Costa Counties.	1.50	1.50
Lewis -Workman and Brod (1997) [30]	MRT: BART	Average home prices decline by about \$1,578 for every 100 ft further from station.	51.74	43.11

Bus Versus Rail Implications for Transit-Oriented Development. Table 7 (Continued)

Study	Transit system	Findings	Standardized proximity premium in present US\$	Standardized proximity premium in 1990 US\$
Lewis -Workman and Brod (1997) [30]	MRT: New York City MTA	Average home prices decline by about \$2,300 for every 100 ft further from the station areas.	75.41	62.84
Voith (1993) [32]	MRT: Philadelphia SEPTA	Finds a premium for single-family homes with access to rail stations of 7.5–8.0% over the average home value.	7.75%	
Cervero and Duncan (2002) [23]	CRT: San Diego	Price increases by 17% in ½ mile of non-downtown Coaster station	84	63.75
Landis et al. (1995) [26]	CRT: CalTrain	Did not find a significant impact on house values from proximity to a rail station. Houses within 300 m of a CalTrain right-of-way sold at a \$51,000 discount.	(170)	(170)
Armstrong (1994) [33]	CRT: Boston MBTA, Fitchburg Line	Single-family residences located in communities that have a rail station have a market value approximately 6.7% greater than those that do not. Also found a property value loss of about 20% for properties located within 400 ft of a commuter or freight rail right-of-way.	6.70%	
Commercial property (dollars per square meter for every meter closer to the station)				
Landis et al. (1995) [26]	LRT: San Diego Trolley	No effect found for commercial impacts	0	0
Weinberger (2001) [34]	LRT: Santa Clara, County Guadalupe line	Commercial space within a ¼-mile of a station received an average of 2.3¢ to 5.0¢ more per square feet than space located more than ¾-mile from a station. Office space sold within a ¼-mile of a station received an average of \$4.87 per square feet more per gross building square feet compared to space located more than ¾-mile from a station.	0.36	0.27
Landis et al. (1995) [26]	MRT: BART	Found no effect for commercial property.	0	0
Nelson (1998) [35]	MRT: Atlanta MARTA	Price per square meter falls by \$75 for each meter away from transit stations. Price rises by \$443 for location within special public interest districts.	75.00	61.07
FTA (2000) [36]	MRT: Washington, D.C.	Price per square foot decreases by about \$2.30 for every 1,000 ft further from station.	0.07	0.05
Fejarang et al. (1994) [37]	MRT: Los Angeles	Commercial space within ½-mile of the rail corridor had an additional \$31 increase in mean sale price per square feet over the mean sales price of a comparable control group outside of the rail corridor, between 1980 and 1990.	0.39	0.34

information provided by some of the studies, only part of the reported proximity effects could be converted to 1990 US dollars in comparable units.

Mixed results have been reported on transit proximity premiums associated with apartment rents [21–24]. Results vary mainly depending on the types of transit technologies. Most studies have found positive transit proximity premiums for single-family homes, with a few reporting negative impacts [25–33]. For instance, Armstrong [33] found that single-family home prices were 6.7% higher in communities with a commuter rail station than in communities without. However, a statistically significant property value loss of roughly 20% was found for properties located within 122 m (400 ft) of the right-of-way. Weinberger [34] argues that the presence of transit is a nuisance and may drive down adjacent property values. They cite the noise generated by transit and believe that transit access allows undesirable people easy access to their neighborhoods. Chen et al. [28] tested the nuisance hypothesis in their study of light rail in Portland, Oregon, but found that the benefits to property values attained from proximity to light rail outweighed the negative effects. As shown in Table 7, most studies have identified positive effects of rail transit on nearby properties although some reported negative effects.

LRT tends to have mixed impacts on commercial properties [22, 23, 26, 34], contrasting to mostly positive effects associated with MRT [26, 35–37]. Nelson's [35] study of the Atlanta MARTA heavy rail line showed a negative gradient of \$75 reduced property value per meter from a transit station, indicating a positive benefit associated with access to transit. Weinberger's study suggest positive impacts on commercial property values resulting from proximity to light rail stations, though no specific capitalization rate is provided. The study by Cervero and Duncan shows that in Santa Clara County, commuter rail had a greater impact on commercial property values than the light rail line. Weinstein and Clower's [38] study of the DART light rail system also suggests appreciable effect on commercial properties in the Dallas area from proximity to light rail.

Data on the effects of BRT on property values are quite limited. Rodriguez and Targa [21] estimated that, in Bogota, Columbia, every additional 5 min of walking time to a BRT station reduced rental price by 6.8–9.3%,

which translates to a premium of US\$0.05 per m² for every meter closer to the station after controlling for the distance to (i.e., the nuisance effect of) the system right-of-way. Also studying Bogota's BRT, Munoz-Raskin [25] confirmed that, in most cases, property values were lower within 5-min distance of the system than those beyond. Cervero and Duncan's [22] study of BRT in Los Angeles found that residential properties near BRT stops sold for less while commercial properties for more. The reason for this negative price effect, according to them, is that the majority of BRT stops are located in redevelopment areas of Los Angeles. In another study looking at how income serves as a determinant in communities' valuing transit, Nelson [10] found that the elevated MARTA heavy rail in Atlanta had positive effects on home values in low-income neighborhoods but negative effects in high-income neighborhoods.

One factor that may partly explain the varying empirical findings above is system maturity [12, 14]. Studies conducted on newly constructed transit systems may not capture the positive valuation of transit on property values because housing markets have not had time to react to transit's presence. Transit ridership may serve as an indication of the magnitude that transit can add to property values, since low ridership indicates that transit is not an amenity to be used [14]. Transit technology also matters, with reliability and speed adding value to the system and in turn being capitalized in property values. Unwanted adjacent uses such as freight or industry will also play an important role by reducing neighborhood quality of life [13].

Density for Bus and Rail Transit

A question of general interest is what land-use densities are needed in order to support specific transit operations. The work by Pushkarev and Zupan [39] remains one of the most influential publications on density and transit uses. They plotted with the logarithmic values of population and trip densities on the horizontal and vertical axis, respectively. The log-log graph exhibits virtually a straight line. Specifically, in the New York Region, trips per square mile by MRT increase from 12 at a residential density of 0.8 dwelling units per acre (or du/ac) to more than

Bus Versus Rail Implications for Transit-Oriented Development. Table 8 Transit supportive densities

Mode	Service	Minimum necessary residential density (dwelling units per acre)	Remarks
Dial-a-bus	Many origins to many destinations	3.5–5	Lower figure if labor costs twice those of taxis; higher if thrice those of taxis
Local bus	Minimum to frequent services; 1/2 mile route spacing; 20–120 buses per day	4–15	Average, varies as a function of downtown size and distance from residential area to downtown
Express bus (BRT) – walk access	Five buses during 2 h peak period	15 Average density over 2 mile ² tributary area	From 10 to 15 miles away to largest downtowns only
Express bus (BRT) –drive access	Five to ten buses during 2 h peak period	3 Average density over 20 mile ² tributary area	From 10 to 20 miles away to downtowns larger than 20 million square feet of nonresidential floorspace
Light rail (LRT)	Five-minute headways or better during peak hour.	9 Average density for a corridor of 25–100 mile ²	To downtowns of 20–50 million square feet of nonresidential floorspace
Metro rail (MRT)	Five-minute headways or better during peak hour.	12 Average density for a corridor of 100–150 mile ²	To downtowns larger than 50 million square feet of nonresidential floorspace

Source: From [39, 40]

60,000 at a density of 200 du/ac. Table 8 shows a typical range of transit supporting densities [39, 40].

Recent studies have confirmed the pattern that Pushkarev and Zupan found 3 decades ago: the closer people live to transit and other services such as shops, the more likely it is that they will utilize the transit and drive less [41, 42]. The study by Frank and Pivo [43] compared travel mode choice among different census tracts with differing levels of employment and population density. They found that transit usage and walking increase as density and land-use mix increase, whereas travel by single-occupancy vehicle (SOV) declines. The relationship between density (employment and population) and mode choice for SOV, transit, and walking displays a nonlinear pattern for both work and shopping trips. Significant modal shifts from SOV to transit and walking occur when employment density increases from 20 to 75 employees per acre or reaches 125 or more employees per acre. Population density needs to exceed approximately 13 persons per acre in order to achieve major modal shifts from SOV to non-driving modes for shopping travel.

The Institute of Transportation Engineers in its 1989 publication suggests that, to support bus service

with headways of an hour, 4–6 du/ac and 5–8 million square feet of commercial/office space in the corridor is needed; for bus service with 30 min headways, 7–8 du/ac and 8–20 million square feet of commercial/office space is needed; and for light rail and feeder bus service density of 9 du/ac and 35–50 million square feet of commercial/office space is desired [44]. Newman and Kenworthy found that densities of at least 12–16 persons/acre are needed to support urban transit [45]. Similarly, another study found that transit use increases sharply when residential density moves from 7 to 16 du/ac [46]. Levinson [47] found that a relationship between mode choice and density was significant only in densities greater than 10,000 persons per square mile. As much as 93% of the transit demand in Portland, OR can be explained by employment and housing densities [48]. Residential densities of more than 80 du/ac were considered highly supportive, those from 46–80 du/ac medium high, those from 20–45 du/ac medium, 6–19 du/ac medium low, and 0–5 du/ac as low in support of transit [49]. Standard bus service can be maintained at 7 du/ac, and significant transit use increases can occur at 10 du/ac and higher [46, 50]. Lawton has also shown that the higher the density found in an area, the more likely

people will walk or take transit and produce less vehicle miles traveled [51].

Some have argued that certain densities of office and other industries can support transit without high-density development [52–54]. Cervero [55] investigated suburban employment densities and found that ride sharing increased by 3.5% for every 5,000 jobs added. Retail and services located near places of employment reduce VMT and prompt workers to utilize transit [56]. Barnes and Davis [57] maintain that commercial land use exerts much more influence on travel choices than do residential densities. Additional work by Cervero has found that suburban employment centers, especially when mixed use is incorporated, prompt the employees to commute via different modes. Furthermore, those living near transit stations are much more likely than others to commute to work by transit [58–60].

Others have emphasized the link between transit usage, car ownership, and centrality instead of transit usage to density [61]. It has been shown that a 10% increase in population centrality (corresponding with higher densities) lowers the chance that a worker drives to work by a margin of 2.1% [62]. Johnson concluded that not only density but density and its spatial relation to the transit stop are both important when evaluating ridership potential [63]. Schimek [64] has argued that, while density matters, its affects are minimal – only providing a 0.7% reduction in auto travel with a 10% rise in density. Another study noted that while density seemed to explain bus usage significantly, it was difficult to properly identify densities, and that destination as well as departure points should be taken into account [65].

Specific densities needed for BRT operation have not been sufficiently identified, although figures for the standard bus-based operations can be borrowed and extrapolated. BRT may perform better in lower-density areas than LRT [66]. In corridors with several medium-density cores but with an overall low-density landscape, BRT’s flexibility may make it more suitable than LRT [67].

Transit analysis conducted by the Florida Department of Transportation has ranked densities as to how they may support public transit (Table 9). Residential densities at 80 dwelling units or more

Bus Versus Rail Implications for Transit-Oriented Development. Table 9 Florida DOT’s assessment of transit supportive densities

<i>Dwelling units per acre</i>	<i>Support level</i>
>80	High
46–80	Medium high
20–45	Medium
6–19	Medium low
0–5	Low

Source: [68]

per acre are considered highly supportive, whereas less than five dwelling units per acre are not transit supportive [68].

Best Practice of Bus- Versus Rail-Based TOD

Curitiba is the capital city of the Brazilian state of Paraná in Brazil. It presents one of the most successful corridor-type TODs on BRT in the world. Curitiba’s BRT system is featured with exclusive rights-of-way, biarticulated buses, tube stations, and land-use zoning coordinated with high-capacity bus corridors (Fig. 2). The system plan is known as the Trinary Model. The model has a two-lane street at the center where the express buses have their exclusive lane. Adjacent to the express lane are two one-way streets moving in the opposite directions. Lots on both sides of the central streets are zoned to develop at high densities. One block from the one-way street on each side of the corridor is a regular two-way street that carries a mix of private vehicle flow and conventional bus services. Five of these roads form a star that converges to the city center. Land farther from the roads is zoned for lower-density developments.

The success of Curitiba’s bus-based corridor TOD is shown by a number of key statistics: as of 2008, there were 340 bus lines, 58 km of busways, 1,100 km bus routes, and 26 terminals. Daily the system serves 380,000 passengers by the corridors and 2.4 million by the network. The BRT operates at a less than 1 min headway in the peak hour, peak directions, with an average speed of 30 km/h for the trunk line and 20 km/h for other routes. More than 70% of commuters ride the bus to work.



Bus Versus Rail Implications for Transit-Oriented Development. Figure 2
BRT-based TOD in Curitiba, Brazil



Bus Versus Rail Implications for Transit-Oriented Development. Figure 3
LRT-based TOD node, Mockingbird Station, Texas, USA

The Mockingbird Station TOD represents the best practice of TODs implemented around a single node of LRT (Fig. 3). Located four miles north of downtown Dallas, the Mockingbird Station is one of the largest on

the Dallas Area Rapid Transit (DART) rail line. Developer Ken Hughes of UC Urban of Dallas initiated and developed the 4-ha project in 2000–2001. Main functions of the TOD site contains 16,536 m² of retail,

restaurant, and cinema space; 12,727 m² of office space, 211 loft apartments; and parking for 1,580 vehicles. The main features of the Mockingbird Station TOD include its combination of adaptive use of historical warehouses with new construction, fine design of streetscape and public arts, and careful organization of pedestrian paths and public as well as private vehicle movement. The success of the Mockingbird Station TOD has proven that a properly conceived TOD can succeed and flourish by serving the adjacent communities, increasing transit use while acting as a catalyst for place making.

Hong Kong's Mass Transit Railway Corporation (MTRC) is one of few successful cases in the world that the rail transit agency is able to fully self-finance system construction and operation by practicing a Hong Kong model of TOD, namely, "Rail + Property" or "R + P" (Fig. 4). Its central idea is to integrate



Bus Versus Rail Implications for Transit-Oriented Development. Figure 4

Tsingyi station: example of Hong Kong's "Rail + Property" TOD model

property development with rail operation and construction such that the profit gained from property development pays the operational and capital costs of the rail system. The main working procedures are as follows. First, MTRC studies development potentials in the area of approximately 500-m distance to the proposed stations. It then obtains land development right from the government for the (re)developable properties. The land cost to MTRC (i.e., land premium income to the government) is estimated based on the no-rail scenario. Next, MTRC specifies development plan for the properties in terms of use composition (residential, retail, green space, transportation, etc.), density (i.e., FAR), and other needed facilities. After the government's approval of the plan, MTRC develops the rail system and the station area in partnership with developers. Because of rail transit availability, property value increases. MTRC then sells properties to individuals or firms, sharing the profits with developers and the government. The MTRC's earnings will be used for maintenance and expansion of rail services as well as other expenses or investments.

MTRC's R + P model proves to offer an all-win solution, at least in the scope of MTRC's services. MTRC benefits from guaranteed funds for service delivery and expansion. To the community, ordinary citizens enjoy high-quality rail services while the share of household expenditure in transportation remains low (9%) [69]. To the developer, MTRC plays a coordinator role, helping reduce start-up costs. The government is a big winner as well. Since 2000 when MTRC went public, the R + P practice has enabled MTRC to operate high-quality rail services without asking subsidy from the government. Furthermore, the Hong Kong government has received a profit (net initial equity contribution) of over HK\$103 billion from its 76% MTRC shares.

Conclusions

Table 10 summarizes modal characteristics of bus- and rail-based transit systems. Main categories of features for comparison include capacity, cost (capital and operating), land-use impacts, and transit supportive densities. For easy reference, their attributes are normalized by using BRT as the main reference.

Bus Versus Rail Implications for Transit-Oriented Development. Table 10 Comparison among major transit modes

	BUS	BRT	LRT	MRT
Capacity: typical peak-hour passengers	1,000–3,000	2,000–10,000	3,000–18,000	13,000–41,000
Capital cost (1990\$ per route mile, millions)		\$10.24	\$26.4	\$128.2
Operating cost (\$ per vehicle revenue mile)	\$3.1	\$3.6	\$9.3	\$6.5
Operating cost (\$ per unlinked passenger trip)		\$1.51	\$2.03	\$1.23
Property impacts: apartment (1990\$ per square meter for every meter away from transit)		\$0.05	\$0.3	\$1.15
Property impacts: single-family home (1990\$ per home for every meter away from transit)			\$0–38	\$43–62
Minimum density (dwelling units/acre)	4	9	9	12
Ratio to BRT				
Capacity	0.35	1	1.65	5.30
Capital cost		1	2.58	12.52
Operating cost (per vehicle revenue mile)	0.86	1	2.58	1.81
Operating cost (per unlinked trip)		1	1.34	0.82
Minimum density	0.44	1.00	1	1.33

The comparisons depicted above indicate that, on average, BRT has the potential to outperform LRT in providing a moderate to high level of service capacity at a moderate level of capital and operating costs in neighborhoods with moderate population and job densities. MRT, although most expensive to build, can achieve over five times the capacity of BRT or LRT and has demonstrated the largest positive impacts on property values in the vicinity of rail stations.

The reviews provided in this entry on the comparative costs, capacities, and land-use impacts of various rapid transit technologies suggest that no simple answer exists to the question. Perhaps no single form of transit will fit all market needs of a community. Each transit technology is efficient when it is in the right place serving the right market. It is more likely the case that all forms of transit systems coexist, each serving a particular market niche. The key is to propose context-sensitive TODs for integrated development transit with land use.

Future Directions

Current TOD practices and studies have largely focused on nodal TODs, that is, the stand-alone TODs around

individual bus stops or train stations. However, many community objectives, for instance, affordable housing provision, job-housing balance, and congestion relief, cannot be well addressed at the individual TOD basis. From a traveler's perspective, whether she/he uses transit depends not only on what the origin can offer but also on what amenities the destination provides. Hence, an important direction for future study is Corridor TOD, which formulates development and implementation strategies at the corridor scale along bus or rail transit routes.

Another future direction is TOD-based value capture for transit financing. Existing TOD initiatives are mostly concerned with physical planning and design of TODs as well as legal and political barriers to TOD implementation. There are successful examples as mentioned above on TOD-based value capturing through integrated transit-land development. How the successful experience can be transferred to cities and countries with different legal, institutional, and financial settings remains a challenge and warrants future research.

Furthermore, the current urban TOD practice can be expanded to other modes of transportation for intercity travel, for example, air, ferry, and high-speed

rail. Stations and terminus for intercity transportation typically have more complex traffic operations than those of intracity transit. A new trend is to develop the station or terminal areas as multifunctional places rather than traditionally as single-function transportation hubs. TOD principles can be applied to these cross-region modes, while their technological complexities require specific consideration.

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